STRATEGY 2017 → 2022 AND BEYOND ↗

Nikhef

National Institute for Subatomic Physics

NIKHEF STRATEGY
2017 → 2022 AND BEYOND

NIKHEF MISSION

The mission of the National Institute for Subatomic Physics Nikhef is to study the interactions and structure of all elementary particles and fields at the smallest distance scale and the highest attainable energy. Two complementary approaches are followed:

1. Accelerator-based particle physics – studying interactions in particle collision processes at particle accelerators, in particular at CERN;

2. Astroparticle physics – studying interactions of particles and radiation emanating from the universe.

Nikhef coordinates and leads the Dutch experimental activities in these fields. The research at Nikhef relies on the development of innovative technologies. The knowledge and technology transfer to third parties, i.e. industry, society and the general public, is an integral part of Nikhef's mission.

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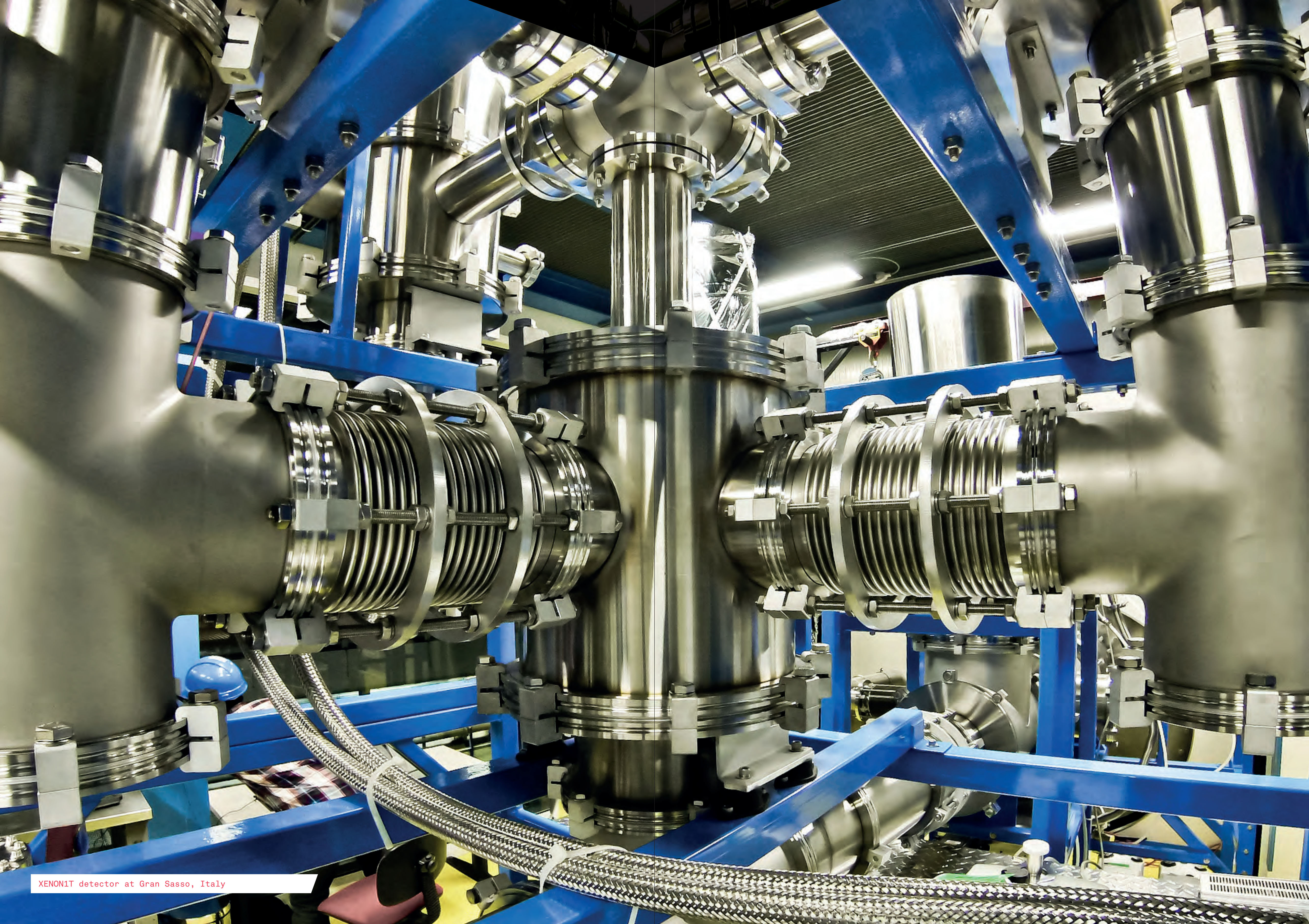


XENON1T detector at Gran Sasso, Italy

INTRODUCTION 01

Over the last few years, Nikhef has been part of historical events: the discovery of the Higgs boson, and that of gravitational waves. The first, though long expected, was truly ground-breaking: a nugget of vacuum, in the form of a fundamental spinless particle, is now known to exist. The second, no less impressive, shows spacetime itself to be dynamical, opening up a whole new research domain.

Stan Bentvelsen, director Nikhef

These two spectacular discoveries give direction to Nikhef's vision for the future, as described in this *Strategic Plan 2017-2022 and beyond*. It was developed on the basis of inspiring discussions with all staff scientists at Nikhef. As an outcome, it has led to further optimisation of Nikhef's scientific portfolio, a well-balanced set of choices to participate in international experiments, and a further developed view on the institute's societal relevance and approach to attracting talent.

The future of particle physics is extremely prosperous as exciting new boundaries in scientific knowledge will be crossed over the next years. However, this process takes time and effort, and results are intrinsically impossible to predict. An excellent knowledge and technology base, together with a long-term vision, is essential to further build and exploit the large infrastructures we need for this type of research.

Nikhef's primary focus is curiosity-driven research. However, Nikhef has always acknowledged the importance of industrial applications and societal gains from fundamental research (*'valorisation'*). Although industry would not be interested in contributing to the discovery of the Higgs boson or gravitational waves, it is indeed interested in the technologies we use to accomplish these type of scientific discoveries.

Particle physics is intimately linked to the advancements of particle accelerators, detection techniques and instrumentation, computing and data analysis. Nikhef, a partnership between five major Dutch universities and the institute at the Netherlands Organisation for Scientific Research (NWO), offers a complete infrastructure to perform experimental particle physics at the highest level. The scientific staff of Nikhef, often closely linked to universities where talent is scouted, is surrounded by excellent engineering, instrumentation and electronics workshops to perform R&D and to build instrumentation.
Data analysis is supported by an in-house computing infrastructure. And, on the other end of the spectrum, the Nikhef theory department provides phenomenology predictions. Nikhef has also shown to be very effective in international 'Big Science' collaborations.

Above all, it's the people at Nikhef that make the institute a success. The enthusiasm of its scientists and engineers, and the energy that they radiate, originate from a deep motivation to learn about the mysteries of the universe and to invent new technologies, and from the sheer pleasure of finding things out.

1A MISSION

As national institute for subatomic physics, the primary raison d' être for Nikhef is to perform research in fundamental particle and astroparticle physics. In the coming years we remain committed to the institute's current mission statement.

Nikhef's strategic agenda for the period 2017-2022 and beyond is based on three pillars. First, we aim to continue the strong involvement in the ongoing experiments at LHC and in astroparticle physics, which we will refer to in this document as 'proven approaches'. Second, we plan to participate in a number of exciting new initiatives, referred to as 'new opportunities', exemplifying the vitality of our research. Third and last, we have set goals beyond the realm of science, concerning our connection to society. This includes outreach, educating talent and nurturing start-ups and innovation. As part of this third pillar we also have the ambition to renovate our building, something that is urgently needed to optimally support our ambitions in all three pillars.

1B PARTNERSHIPS AND EMBEDDING

Nikhef has a number of national and international partners. CERN is by far the most important one; our institute serves as a bridge between CERN and our university partners. In the coming years, CERN will continue to play a pivotal role for the institute. A large part of the strategic agenda deals with the physics uncovered at the Large Hadron Collider (LHC) through the ATLAS, LHCb and ALICE experiments. Apart from CERN, our international partners with long-term commitments are a number of consortia in experimental astroparticle physics. These experiments are located in Italy, France and Argentina, with one experimental programme at the University of Groningen in the Netherlands. Further partnerships of Nikhef are found all over Europe, the topics of which include detector R&D, computing infrastructure and theory phenomenology. Smaller-scale partnerships typically concern dynamic community exchanges and an extensive visitor programme that all generate lively discussions.

The national partners of Nikhef are, first of all, its five partner universities: University of Amsterdam, VU University Amsterdam, Utrecht University, Radboud University and the University of Groningen. In addition, Nikhef has close ties with Twente and Delft Universities of Technology, the Universities of Leiden and Maastricht, and KVI-CART[1] by means of R&D collaborations, research exchanges, special professorship appointments, lecturing and student exchanges. We actively collaborate with the astronomy community, e.g. via NCA[2], GRAPPA[3] at the University of Amsterdam and IMAPP[4] at the Radboud University. We have close connections and expert exchange with SRON[5] for LISA[6] activities and chip design. Further collaborations are with TNO[7] and NIOZ[8] for the KM3NeT programme. We have close contacts with a large number of industries and start-up companies, and industrial research collaborations with Shell, PANalytical, ASML, Tata Steel, Photonis and a number of computing hardware vendors. Various HBO[9] schools are involved via student internships at Nikhef, and we plan to further strengthen these ties by installing a lector position. Recently, an active collaboration with the Province of Limburg was started

1 KVI-CART, Center for Advanced Radiation Technology.
2 NCA, the Dutch National Committee for Astronomy.
3 GRAPPA, the center of excellence for Gravitation and Astroparticle Physics at the University of Amsterdam.
4 IMAPP, Institute for Mathematics, Astrophysics and Particle Physics, Nijmegen.
5 SRON, Netherlands Institute for Space Research.
6 LISA, Laser Interferometer Space Antenna.
7 TNO, Netherlands Organisation for Applied Scientific Research.
8 NIOZ, Royal Netherlands Institute of Sea Research.
9 HBO, Higher professional education.

on the topic of the Einstein Telescope. Further, the institute has numerous outreach connections with primary schools, secondary schools and societal clubs and associations.

This Nikhef strategy also serves as input to the European Strategy Update of Particle Physics that will take place between 2018-2019 to set the long-term agenda for CERN. Furthermore, it is in line with the AstroParticle Physics European Consortium (APPEC) roadmap, which will be published later in 2017 and contains a number of recommendations for the field of astroparticle physics.

Another key stakeholder for Nikhef is formed by the general public. Fundamental research and innovative techniques strongly resonate with the general audience. This is demonstrated by Nikhef's involvement in a large number of outreach activities, radio and television items, newspaper stories, etc. The Dutch National Research Agenda, driven by questions of the general Dutch public and a vast number of organisations in the Netherlands, includes a 'route' dedicated to "Building blocks of matter and fundaments of space and time", which has already gained a lot of attention. The societal relevance and viability is further highlighted by the above-mentioned spin-offs, valorisation projects and public-private partnership activities with industry. Innovation along the lines of the *Topsector* policy (specifically, the Topsector 'High Tech Systems and Materials') has been a key driver over the past few years and, for the years to come, ambitions to innovate will keep finding fertile grounds at Nikhef.

As part of the Netherlands Organisation for Scientific Research (NWO), Nikhef coordinates particle physics in the Netherlands and provides a bridge between the international experiments and partner universities. With the recent overhaul of the organisational structure of NWO, all NWO institutes, including Nikhef, are now part of the Institutes Organisation of NWO (NWO-I). The former NWO science divisions have been clustered into domains and each domain organisation is responsible for the primary processes of granting and policy development within that area. One of the challenges is to align the strategy of Nikhef with that of the NWO Science domain, called ENW. Long-term planning in this ENW domain is essential for pursuing a strategic agenda and to ascertain the necessary long-term commitments in international experiments that are characteristic for our 'Big Science' projects.

1C SCIENTIFIC CHALLENGES

UNDERSTANDING THE UNIVERSE IN TERMS OF ITS ELEMENTARY PARTICLES AND FIELDS

Both the discovery of the Higgs particle and the observation of gravitational waves are ground-breaking scientific achievements. One has already been celebrated with the Nobel Prize in Physics (2013, Peter Higgs and François Englert). In both, Nikhef played a major and visible role, with top-ranked scientists and dedicated instrumentation[10].

The discovery of the Higgs particle describes the origin of mass for all known elementary particles. At the same time, the identity of the Higgs particle and the whole underlying Higgs mechanism are absolute unique and mind-boggling. They may give an adequate description for the mass of elementary particles, but lead to conceptual problems in our understanding of their behaviour. The Higgs potential in the Standard Model introduces new questions on the large-scale structure and stability of our universe, the differences between matter and antimatter, and the flavour structure of the model. Effectively, we do not have a clue how the sheer existence, origin and evolution of our universe can be described in terms of its building blocks. The Standard Model of particle physics, albeit a logic and successful model of the infinitely small, is seriously falling short.

By extracting new knowledge and understanding from particle collisions in accelerators, and by studying the particles and forces that we observe in our cosmos, researchers shed light on the biggest and most intriguing questions about the elementary particles and fields that make up our universe. This is exactly the scientific adventure of Nikhef.

HARVESTING TIMES

The journey into the heart of matter is extremely challenging and exciting. International collaborative efforts have resulted in a unique set of experiments that all have the potential to uncover what physics lies beyond the known Standard Model. Most of the experiments have taken many years to prepare. Now it is time to harvest.

[10] The separate SEP evaluation document lists the contributions of Nikhef in these endeavours.

The Large Hadron Collider (LHC) at CERN delivers record luminosities, leading to a torrent of scientific results. With the Higgs particle in hand, nature will be unveiled by the LHC with unprecedented potency. This journey continues with the excitement of knowing that new, unknown physics must lie beyond the corner of our current knowledge, ready to be discovered. We may not know the look and feel of this new physics, but we do know that we have the right infrastructure in hand to make a discovery. A first clear signal of new physics will imply a revolution in the way mankind perceives the fundamental building blocks of our universe. At the LHC, both the ATLAS and LHCb experiments probe the existing physics with unprecedented accuracy, and search for new phenomena. With every enlargement of the LHC data set, they probe further into the unknown. This is also the case for the new eEDM programme at Nikhef, which aims to detect the electric dipole moment of the electron using a highly sensitive experiment. The ALICE experiment at the LHC studies the quark-gluon plasma using lead-lead collisions, recreating the state of the universe just after the Big Bang. The power of the LHC and its detectors is so large, that a lot is learned about our nature even when no new phenomena are discovered.

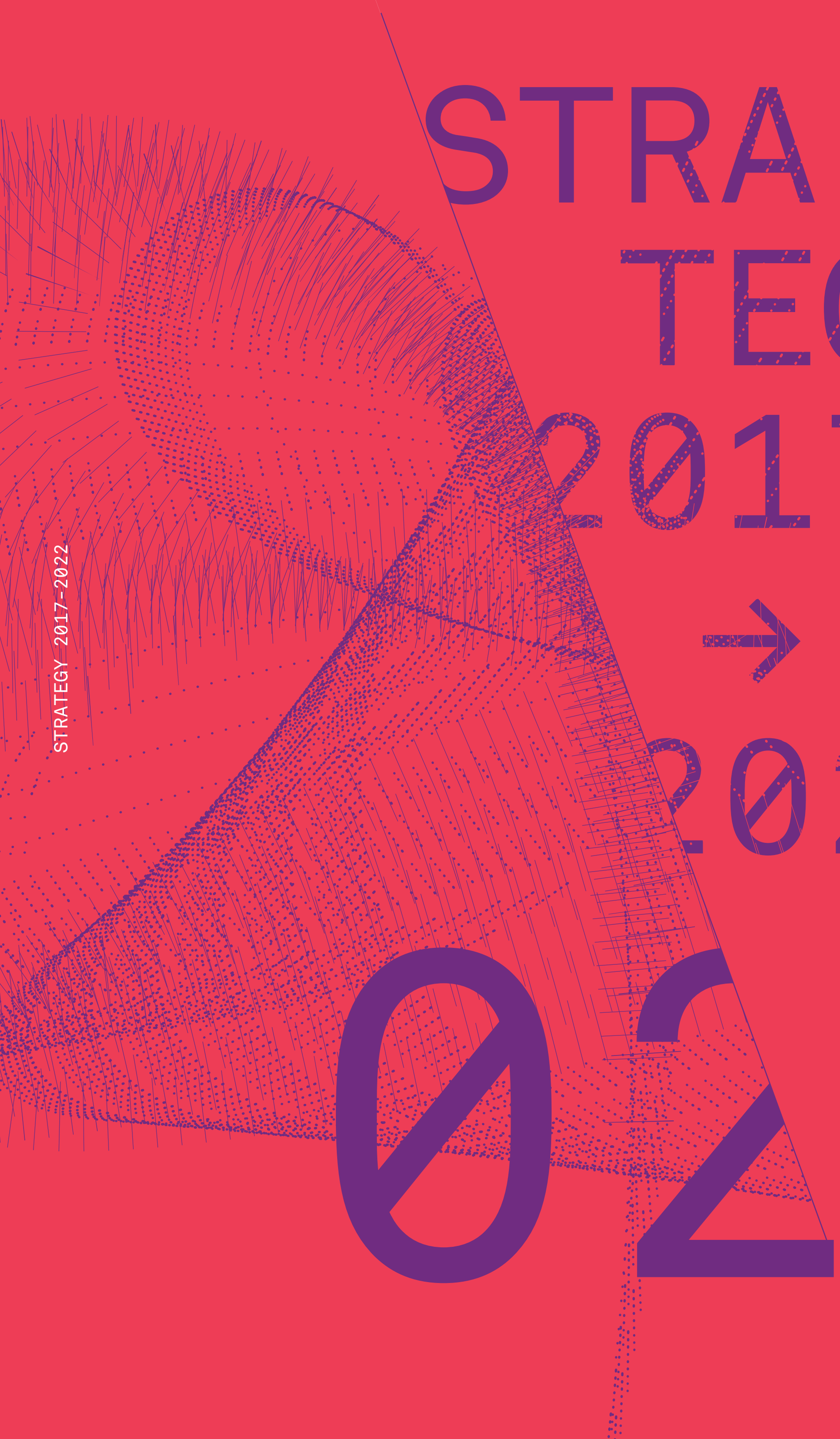
Astroparticle physics delivers equally relevant results. In the disclosure of the fundamental building blocks of the universe, Nikhef is making crucial contributions to detecting neutrinos in the deep Mediterranean Sea by designing and constructing the KM3NeT detector. KM3NeT contains a rich programme for searches for dark matter, neutrino properties and astrophysical sources. Gravitational waves provide an entirely new way to observe the universe as the vibrations of space-time can be interpreted as *listening* to our universe. The cataclysmic events that generate these gravitational waves deal with gravity in an unexplored strong-field regime. Nikhef is deeply involved in gravitational waves and has strong ambitions in this field for the next decades. Direct detection of dark matter is pursued with the XENON1T/nT detector in Gran Sasso, Italy. Ultra-high-energy cosmic rays are being studied with the Pierre Auger Observatory in Argentina, providing another ingredient of the multi-messenger approach to astroparticle physics.

SCIENCE DRIVERS

Nikhef is selective in the experiments it chooses to participate in. We have the ambition to be a key player in the construction, to bring relevant expertise and to fully exploit the data analysis. Foremost, the experiments have to be relevant to answering the most challenging questions of modern particle physics. The experimental and theoretical science drivers are:

The Higgs particle	All properties of the Higgs particle are fixed by the Standard Model. The Higgs particle may be the portal to physics beyond the Standard Model (BSM).
Gravitational waves	With the first detection of gravitational waves, we have unlocked a new research field with implications for particle physics, cosmology and astro (particle) physics.
Discovery of new particles and symmetries	A discovery of new underlying symmetries and particles has immense implications on our understanding of the building blocks of our universe.
Dark Matter	Numerous astronomy and cosmological observations led to the conclusion that a large fraction of matter is invisible. The identity of this ‘dark matter’ remains a mystery.
Neutrinos	A number of fundamental properties of the neutrino family are still unknown today.
Quark-gluon plasma	The many-particle system of quarks and gluons reveals new phenomena that are thought to have occurred during the very early stages of our universe.
Matter - antimatter differences	The Standard Model does not explain the dominance of matter over antimatter in our universe.
Cosmic messengers	Concerns the study of the origin and acceleration mechanism for ultra-high-energy cosmic rays, charged particles of various kinds, neutrinos and photons.
Electron properties	A measurement of a non-zero electric dipole moment of the electron would be a direct proof of physics beyond the Standard Model.

Instrumentation, engineering and computing are the *enablers* for these science drivers, and play a fundamental role. Work in this area constantly pushes the limits of what is possible.



02 STRATEGY 2017 → 2022

The Nikhef strategy for the coming years 2017-2022 contains the pillars "proven approaches", "new opportunities" and "beyond scientific goals" as detailed in this chapter.

Pillar I Proven approaches

- → Construct the upgrades and exploit the physics of the LHC experiments ATLAS, LHCb and ALICE
- → Build KM3NeT phase 2.0 and exploit neutrino (astro)physics
- → Exploit the astroparticle experiments Advanced Virgo, XENON1T/nT and the Pierre Auger Observatory
- → Fully utilise the theory, detector R&D and computing activities at Nikhef

Pillar II New opportunities

- → Determine the electron electric dipole moment with world-class precision
- → Prepare for a new era of high-energy accelerators
- → Strengthen and exploit the thematic connections between individual scientific programmes
- → Prepare a bid to host the Einstein Telescope in the Netherlands

Pillar III Beyond scientific goals

- → Establish further links with industry and other third parties in terms of transfer of knowledge generated at Nikhef
- → Attract and train a new generation of scientists and engineers
- → Modernise the Nikhef branding and building
- → Inspire and nurture scientifically aware general audiences

The Einstein Telescope in the Netherlands

The Einstein Telescope is a third-generation ground-based interferometer that is envisioned to generate unique scientific contributions to gravitational wave research for more than half a century. It will be of iconic status and a focal point of attraction for fundamental physics, astronomy, cosmology as well as innovative industry. By assembling key parties including the astronomy community and innovative industry partners, Nikhef will explore the possibility to prepare a bid to host the Einstein Telescope in the Netherlands.

2A PROVEN APPROACHES (PILLAR I)

LHC PROGRAMME

The physics of the LHC programme is extremely rich, and it will take many years to exploit its full potential. The LHC typically has an annual cycle with short winter stops, interleaved with a few shutdown periods to account for installation of upgrade detectors and accelerator infrastructures.

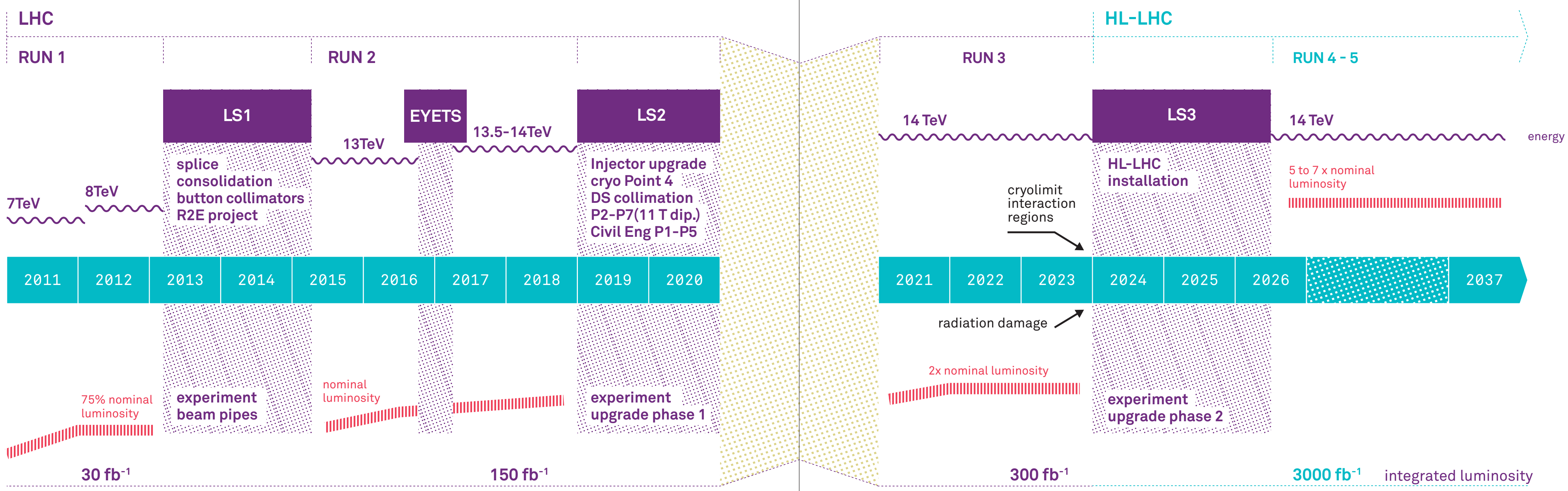
The running schedule of LHC is currently organized as follows

→ 2015 – 2018: Running period	Run-2
→ 2019 – 2020: Long shutdown	LS2
→ 2021 – 2023: Running period	Run-3
→ 2023 – 2026: Long shutdown	LS3
→ 2026 – 2030: Running period	Run-4; start of the HL-LHC period
→ >2030: Long shutdown	LS4 and Run-5 afterwards

As part of the LHC programme, we discuss three LHC experiments (ATLAS, LHCb and ALICE), identifying both opportunities and challenges. For each of the experiments we describe the Nikhef goals for 2017-2022.

FIGURE 01 **LHC / HL-LHC plan**

Running schedule of the LHC for the period 2011 to 2037, including the planned upgrade from LHC to high-luminosity (HL) LHC.



MISSION

To study the Higgs particle responsible for the generation of mass and to search for physics beyond the Standard Model, such as supersymmetry, large extra space-time dimensions, or unexpected phenomena.

LHC → ATLAS

Technical challenges

The LHC will steeply increase its beam intensities (luminosity) over the next decade, increasing for example the Higgs sample size 10-fold with respect to Run-1 in 2020 and more than 100-fold by 2030. The principal technological challenge of ATLAS is to be able to deal with the corresponding increase in radiation pressure, with the increase in particle flux in the readout and trigger systems, and with the subsequent data and analysis processing. To this end, several detector components close to the interaction point will be replaced; Nikhef will contribute here by assembling a new inner tracker end cap and developing new radiation-hard readout chips for the pixel detector. Nikhef is also co-developing the new Felix readout system that will be rolled out to the muon system in 2019 and to all of ATLAS in 2023.

Research opportunities – (1) searches for new particles

The clearest discovery of new physics is the direct detection of a new fundamental particle. Such a discovery is the holy grail of experimental physics because it is unambiguous and gives immediate information towards undiscovered fundamental physics and towards the design of nature at a hitherto unprobed energy/distance scale. However, it is not *a priori* clear how a new fundamental particle could manifest itself in the detector, in other words, what its *signature* will be. A multitude of competing theories predict a wide range of signatures in the detector. The window of opportunity for discovery is wide and large but also diffuse, and a breakthrough may not be immediate.

The present focus in both experimental and theoretical efforts is on 'easy' signatures that are in discovery-reach with the data volume that is expected to be delivered by the LHC up to the end of 2018. The analysis strategy of Nikhef in this period is to focus on predictions of well-established theoretical extensions of the Standard Model that provide solutions for its shortcomings such as the absence of candidates for dark matter and its intrinsic instability at high energies ('the hierarchy problem'). Examples of these theories include supersymmetry scenarios that favour strong production mechanisms, but also generic dark matter models and extended Higgs sector models. Nikhef has a long-standing expertise in these analyses.

In the longer term, as the LHC delivers ever more data, it will be possible to also test 'difficult' scenarios that for the new particles either predict extremely low production rates (e.g. weakly produced supersymmetry) or decay signatures that are experimentally very hard to detect. These difficult scenarios are not *a priori* less plausible, but will only become of experimental and theoretical interest once sufficient data is available to probe them. The Nikhef long-term strategy for new particle searches is to build on existing analysis expertise and to closely collaborate with the theory and astroparticle physics communities to identify the most promising search signatures for the long-term (beyond 2020). Rare signatures and signatures that are difficult to reconstruct may only be discovered in ATLAS beyond 2025.

Research opportunities – (2) precision measurements

New physics may also manifest itself through modified properties and interactions of known particles: fundamental particles might turn out to be composites, new massive particles could contribute indirectly through loop processes, all affecting properties and interactions of known particles.
The Higgs boson provides the most fertile hunting ground for such studies as it represents both the least tested and the most interesting sector of the Standard Model. Open questions include: *Is the Higgs boson a fundamental or composite particle? Are there multiple Higgs bosons? Is the Higgs mechanism responsible for the mass of all generations of fermions? Is the Higgs potential really of the form of a Mexican hat? Is the Higgs boson a portal to new physics?* These pivotal questions are now all unanswered, but will be answerable with a detailed analysis of the full LHC dataset. Significant progress is expected over the next years: by 2020, the observation of the rare decay of Higgs bosons into muons will be discovered, and observations of the rare production of Higgs bosons in association with a top quark pair will provide the first direct probe of the Higgs-top coupling strength, the Higgs coupling that appears

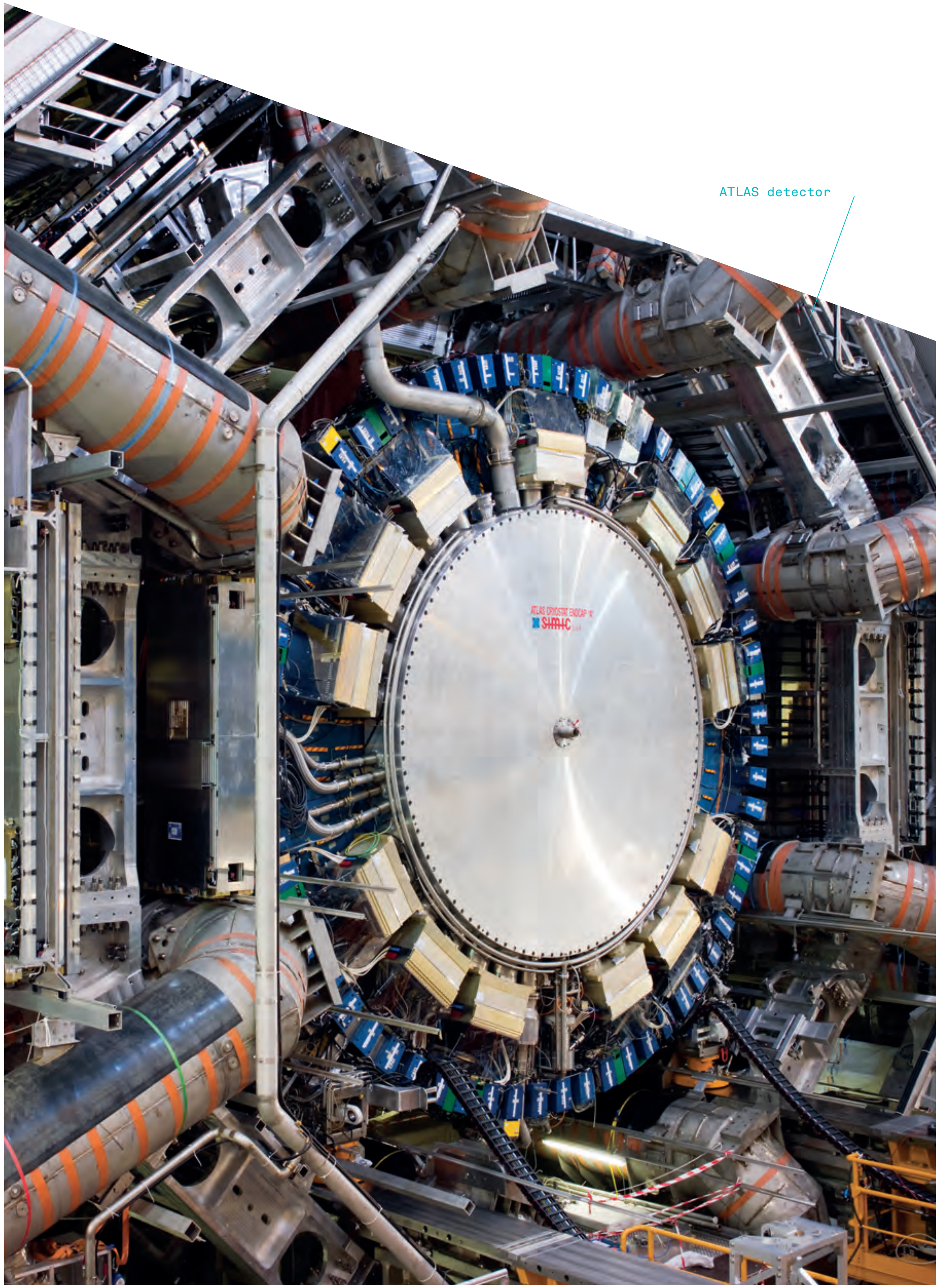
tantalizingly close to its natural value of one. Between now and 2025, all Higgs coupling measurements will continually improve; no channel is predicted to be strongly dominated by limiting systematic uncertainties.

The Nikhef strategy for Higgs physics in the next years is to continue its comprehensive programme of both measuring key individual Higgs decays and developing unified interpretation frameworks to describe all Higgs data. The LHC Higgs physics programme has a life span well beyond 2025 into the era of the High-Luminosity LHC (HL-LHC, see Figure 1). In particular, rare Higgs decays and Higgs production in exotic regimes will continue to be statistics-limited at the HL-LHC and the precision of Higgs property measurements will continue to be improved. Ultimately, Higgs self-couplings –the rarest of Higgs processes– will come into reach. Prospects for this very challenging measurement of the ultra-low-rate di-Higgs production are improving with new analysis techniques and will elucidate the most enigmatic yet essential aspect of the Higgs sector: the existence of a Higgs potential in the form of a Mexican hat.

Finally, the ultra-abundant production of top quarks and vector bosons already offers opportunities to perform high-precision measurements of the top quark mass and the structure of the *Wtb* vertex. It also opens new opportunities to study ultra-rare lepton flavour-violation processes in the decay of vector boson and τ leptons. The Nikhef strategy for the next years here is to focus on anomalous coupling effects in the *Wtb* vertex and on lepton flavour violation in τ leptons and W and H boson decays.

ATLAS GOALS 2017-2022:

- → Measure couplings and CP-properties of the Higgs particle, study Higgs production in exotic regimes, develop unified interpretation of Higgs measurements.
- → Search for beyond-the-Standard-Model (BSM) physics: supersymmetry and lepton flavour violation
- → Study interactions of the top quark
- → Upgrade DAQ system with Felix in LS2, construct an ITk strip detector end-cap to be ready for installation in LS3



ATLAS detector

MISSION

To search for new particles and interactions that affect the observed matter-antimatter asymmetry in the universe, by making precision measurements of B-meson decays.

LHC → LHCB

The ambition of the LHCb collaboration is to further extend the physics programme to become a truly general-purpose experiment in the forward direction. To pursue, at the same time, flavour physics at the intensity frontier and to widen the programme further to include QCD, electroweak and heavy-ion physics, the LHCb upgrade detector will be enhanced to operate at a factor of five higher collision rates. While the upgrade detector is currently under construction, an ambitious project is currently on the drawing table to exploit forward physics during the HL-LHC era. The Nikhef group intends to keep a prominent role in the detector upgrade projects. The group has taken a leading role in (1) constructing parts of the VELO pixel detector, (2) building and designing elements of the Scintillating Fiber Tracker, and (3) designing the High-Level Trigger. These contributions of Nikhef to the LHCb detector upgrades are described in the following.

1 The construction of half of the VELO detector-modules will take place at Nikhef and is expected to start in the winter of 2017-2018. Nikhef also constructs the vacuum encapsulation of the new detector (the “RF-box”), of which a prototype to encapsulate the first detector-half has already been produced. The VeloPix readout chip, required for the 40-MHz read-out, has been designed by Nikhef in collaboration with CERN, and will be further commissioned.

2 For the Scintillating Fiber Tracker, Nikhef designs and constructs the end-pieces of the detector modules that include the so-called cold-box and front-end electronics box. In the cold-box, the SiPM detectors will be operated at a temperature below -40°C to keep dark currents sufficiently low. In addition, 20% of the 5-m-long detector modules of the tracker will be produced in the main Nikhef cleanroom facility. For the read-out system, Nikhef designs the master board hosting the data serializers and transmitters.

3 The upgrade High-Level Trigger will scale to systems with many cores, requiring so-called multi-threaded operation and dynamic scheduling. Nikhef has contributed the Gaudi Functional design, which enforces individual algorithms to be implemented thread-safe. In addition, Nikhef has led the way by demonstrating how to utilize vector units, which are crucial to attain the performance required for the upgrade.

The physics analysis strategy of Nikhef is on the one hand of a long-term nature, while on the other hand it is subject to constant evaluation and updates when new funding resources are obtained. For the remainder of the LHC Run-1 data taking, we will continue to perform CP-violation measurements, albeit enriched with new decay channels, including Penguin control studies with the help of the Nikhef theory group. The topic of very rare decays and flavour violating decays will be further exploited focusing on the relative rate of $B_d \rightarrow \mu^+\mu^-$ and $B_s \rightarrow \mu^+\mu^-$ events, adding a precision measurement of the effective lifetime observable, and on searches for flavour-violating rare decays. For semileptonic decays, our focus will shift from measurements of CP-violation to lepton non-universality tests. Finally, the search of long-lived particles will be continued through the NWO-Vici funding scheme[11]. At the same time we will venture into new and improved tracking, vertex and jet-reconstruction algorithms.

LHCB GOALS 2017-2022:

- → Study CP violation in B decays, test the CKM paradigm
- → Search for rare decays, in particular $B_d \rightarrow \mu^+\mu^-$ and $B_s \rightarrow \mu^+\mu^-$
- → Perform lepton non-universality tests
- → Contribute to detector upgrades for LS2: VELO pixel detector, Scintillating Fiber Tracker, High Level Trigger

[11] Vici is an excellence-based personal grant, part of NWO’s Veni-Vidi-Vici Talent Scheme. It gives senior researchers the opportunity to build up their own research group, often in anticipation of a tenured professorship.

LHCb detector

MISSION

To study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected. Particles and jets produced in collisions of heavy nuclei are measured in detail (and compared to proton-proton collisions) and phenomena such as elliptic- flow and correlations of charmed hadrons or di-jets are studied.

LHC → ALICE

The physics programme of ALICE is clearly defined for the coming period. Measurements to be performed are: (1) the elliptic flow of a variety of identified particles as a function of momentum and collision centrality, (2) the energy loss of partons via suppression of inclusive hadrons and correlations of hadron pairs and via the modification of jets, and (3) heavy-quark production via charmed and bottom hadron reconstruction and via their decay electrons, including the elliptic flow and energy loss of those particles carrying heavy flavour. Elliptic flow is sensitive to pressure gradients in the initial state and thus probes the equation of state. Performing the measurement with identified hadrons provides important mass-dependent information, which constrains the fluid velocities in the final state. Jets and heavy quarks are produced in hard scatterings in the initial collision and probe the medium density as they propagate outwards.

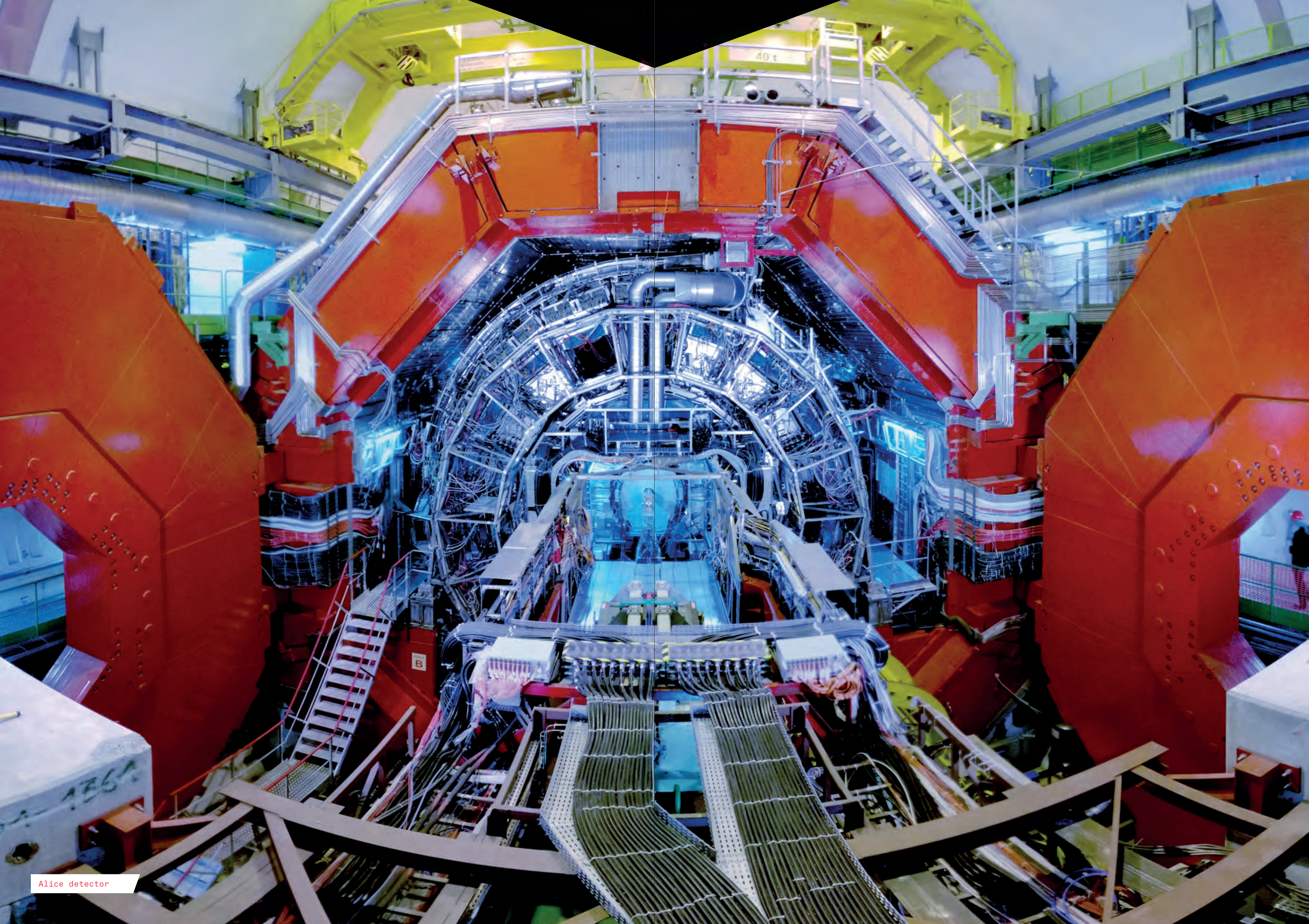
To make full use of the future high luminosity in heavy-ion collisions, the ALICE collaboration has proposed a strategy for upgrading the central ALICE detector. As a result of this upgrade, the interaction rate will be almost two orders of magnitude larger than what ALICE is currently able to handle. For many of our observables, traditional methods for triggering cannot be used. The upgraded ALICE detector must therefore be able to record every collision, which amounts to about 10^{10} interactions and an integrated luminosity of 10 nb^{-1}. This large sample of recorded events will allow us to perform the measurements pursued at Nikhef with sufficient statistical accuracy.

In addition to the increased luminosity, a significant improvement in the reconstruction of heavy quarks is required for our physics programme. This is achieved by improving the accuracy of the measured distance-of-closest approach between a particle track and the primary vertex. For this purpose, a new, high-resolution, low-material-thickness Inner Tracking System will be built. Detailed simulations have shown that the improvement in the secondary-vertex resolution, together with the significant increase in statistics are sufficient to address the main questions about heavy-flavour thermalization and in-medium energy loss.

Over the next years, we will develop the tools and finalize the design for the inner silicon tracking detector and build part of it at Nikhef and Utrecht University. After the next large shutdown LS2 (around 2021) we will start to collect data with this new detector until the next long shutdown (LS3, probably starting in 2024 and likely to last 2-3 years, all depending on how well the LHC operates). This will provide a wealth of new data and will allow us to better answer many of the open questions in our field. The Nikhef group is currently well positioned to take advantage of this opportunity and maximize the output of our investment. For the period after the long shutdown of 2025 we will additionally pursue a possible detector upgrade for the ALICE experiment that aims to measure the effects of gluon saturation. A forward electromagnetic calorimeter, which is currently being studied, is likely the optimal detector for such an upgrade. For this detector, we are collaborating within the CALICE detector R&D collaboration.

ALICE GOALS 2017-2022:

- → Determine the elliptic flow of identified particles
- → Study the energy loss of partons in the quark-gluon plasma
- → Measure heavy-quark production
- → Design and build inner silicon tracking detector for installation in LS2



Alice detector

ASTROPARTICLE PHYSICS (APP)

Astroparticle physics (APP) will continue to be the field where Nikhef puts in a large effort. We exploit a number of successful research lines in neutrino physics, cosmic rays, dark matter and gravitational waves, which currently take up approximately a third of our resources. This balance between accelerator physics (LHC) and APP activities will remain roughly constant over the period 2017-2022. In the scenario that the Einstein Telescope will be hosted by the Netherlands an increase of the mission budget is needed to match the exploitation of this new international infrastructure.

We describe the physics strategy of the APP experiments (KM3NeT, Pierre Auger, XENON1T/nT, Virgo and ET) in the next sections. Before doing so, we note that there are also APP activities and infrastructures in which Nikhef would like to participate but lacks sufficient resources:

→ Most prominent is the planned Cherenkov Telescope Array (CTA), which will detect high-energy photons from intergalactic sources. The physics case is clear: together with neutrinos, charged particles and gravitational waves, the CTA would complete the multi-messenger astroparticle activities of Nikhef. In addition, the CTA has a compelling dark matter particle programme. We welcome Dutch participation in the CTA, for example initiated by our astronomy colleagues.

→ The same can be said about research on the Cosmic Microwave Background (CMB). This topic is interesting and has the attention of a number of staff scientists at Nikhef. However, Nikhef does not have the resources to participate through an experimental programme of sufficient strength. CMB research is highly specialized and will need a large effort, both in manpower and investments, to make a visible impact. This can only be realized with an increase of the mission budget.

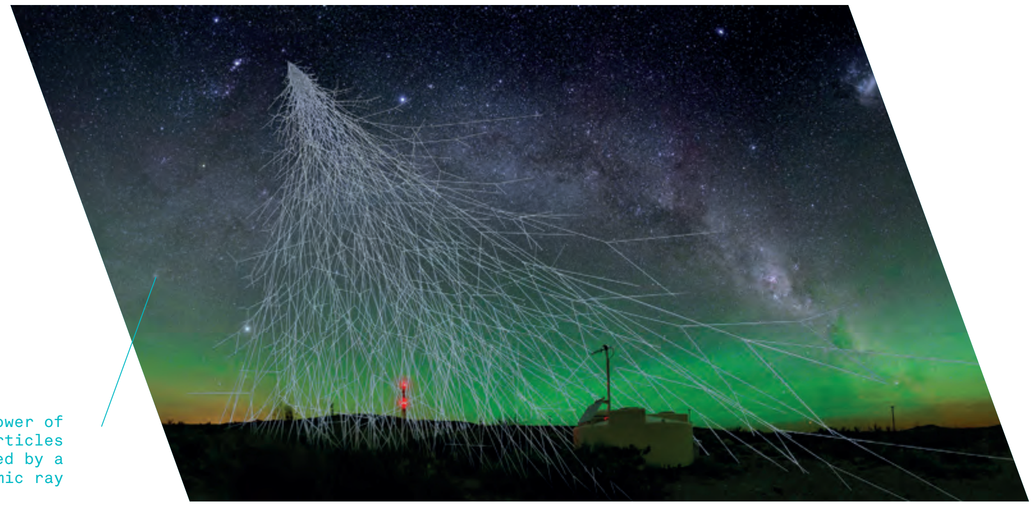
Discussions among the APP community, that traditionally originates from the particle physics and astronomy disciplines, are coordinated in the Netherlands by the Committee for Astroparticle Physics in the Netherlands (CAN). The CAN organizes lively discussions and has produced a roadmap with priorities. For a large part, these match the priorities of Nikhef, but further optimization of the interplay between astronomy and particle physics is needed. CAN is the right platform to strengthen this relationship.

APP GOALS 2017-2022:

→ Develop a national programme on gravitational wave research encompassing Virgo, LISA and the Einstein Telescope, with the CAN binding the APP community.

→ Develop, together with the CAN, a coherent approach to multi-messenger astrophysics and APP by combining information from gravitational waves, cosmic rays, neutrinos and potentially high-energy photons.

The recommendations of the European funding agencies are formulated in the APPEC roadmap update, to be published in September 2017. The APP portfolio of Nikhef corresponds to a strategic selection of preferred experiments.



Shower of particles induced by a cosmic ray

MISSION

To discover neutrino sources in the universe and to study the properties of neutrinos. The observation of cosmic neutrinos will provide information about the origin of cosmic rays, the mechanism of particle acceleration and transient astrophysical phenomena.

APP → NEUTRINO TELESCOPE KM3NET

In the coming years, the construction of KM3NeT-2.0 will commence, seamlessly continuing on from the completion of phase 1 of the project. Full completion of the KM3NeT infrastructure is expected in 2021.

The KM3NeT technology can be used to study fundamental particle physics at GeV energy scales. Using atmospheric neutrinos, which are copiously produced by interactions of cosmic rays with the atmosphere, a densely instrumented section of the KM3NeT infrastructure (named KM3NeT/ORCA) will be used to make detailed studies of the neutrino oscillations. The primary aim is to establish the neutrino mass ordering: the as-of-yet unknown pattern of neutrino masses, which has far-reaching implications for future neutrino oscillation experiments, experiments to prove neutrinos are Majorana particles, and cosmology. For this, the matter effect due to the presence of electrons in the Earth has to be resolved, which requires a large sample of neutrinos. Upon completion in 2021, KM3NeT/ORCA will measure about 50.000 atmospheric neutrinos per year, which will allow for the mass hierarchy to be established in about 4 years of operation (maybe sooner, depending on the value of the mixing angle). In addition, KM3NeT/ORCA will make other contributions to the field of neutrino oscillation physics, such as a precise measurement of θ_{23}, Δm_{23}^2 and a study of the unitarity of the neutrino-mixing matrix.

The discovery of a flux of very-high-energy (PeV) cosmic neutrinos by the IceCube experiment three years ago, has triggered a revolution in the field of astroparticle physics. The neutrinos have been shown to be of cosmic origin, but the associated astrophysical source objects could not be identified due to the limited directional accuracy of the telescope. The identity of the astrophysical neutrino sources, and thereby of the sources of high-energy cosmic rays, is now one of the main research questions in APP. Candidates include spectacular astrophysical objects like active galactic nuclei, starburst galaxies, and (galactic) supernova remnants. Using KM3NeT/ARCA, we will be able to provide an independent 5-sigma confirmation of the neutrino signal within one year. Moreover, we will study the point of origin of each neutrino in the sky with a factor 20-100 (depending on the neutrino flavour) better resolving power. This puts KM3NeT in an excellent position to identify the sources of cosmic neutrinos. At the same time, cosmic neutrinos offer a way to study the properties of neutrinos themselves at energy scales, and over distances, that are completely unattainable using earth-based neutrino beams. The study of the ratio of the three neutrino flavours arriving on Earth offers access to exotic scenarios, like decaying neutrinos, and allows for measurements of the CP-violating phase.

KM3NET GOALS 2017-2022:

- → Complete the KM3NeT-2.0 detector
- → Determine the neutrino mass hierarchy and neutrino oscillation parameters
- → Detect PeV neutrinos and search for point sources
- → Search for BSM physics in cosmic neutrinos

Digital Optical Module with 31 PMTs

APP → DETECTING GRAVITATIONAL WAVES THROUGH ADVANCED VIRGO, ET AND LISA

MISSION

To detect and study gravitational waves (ripples in the fabric of space-time) that are produced by violent events throughout the universe.

Nikhef intends to keep and extend a prominent role in gravitational waves research. Thus far, we have taken a leading role in the upgrade of Advanced Virgo, while contributing to future gravitational wave experiments, such as the Einstein Telescope (ET) and the Laser Interferometer Space Antenna (LISA).

Advanced Virgo: While the full commissioning phase of Advanced Virgo has started, with the initial goal of participating with the two Advanced LIGO detectors in the first joint Observation Run in 2017, a mid-term further upgrade of the interferometer has been planned. Besides the addition of a frequency-independent squeezer for the reduction of the quantum noise (where Nikhef intends to contribute three MultiSAS-type vibration isolation systems), a Newtonian noise-cancellation system will be implemented. Newtonian noise, caused by seismic noise inducing mass density fluctuations in the surroundings of the detector test masses, cannot be shielded and can only be mitigated by subtraction techniques using the measured seismic fields as input. Nikhef is deeply involved in this endeavour, which can be considered a path-finding experiment for such a technology towards the third generation of detectors, such as the Einstein Telescope.

Einstein Telescope: The Einstein Telescope (ET) is a new infrastructure project that is supported by APPEC (2017), included in the Dutch Roadmap for Large-scale Scientific Infrastructure (NWO; 2016), supported by the Royal Netherlands Academy of Arts and Sciences review (KNAW; 2016), and listed as *gamechanger* in the Dutch National Research Agenda (NWA; 2017). Scientists from Nikhef actively investigate the possibility of hosting the Einstein Telescope in the Netherlands. It will be an underground international facility containing cryogenic interferometers with 10-km arms.

LISA: The Laser Interferometer Space Antenna (LISA) is a European Space Agency mission designed to detect and accurately measure gravitational waves from astronomical sources. The LISA concept has a constellation of three spacecraft, arranged in an equilateral triangle with 2.5 million-kilometre arms flying along an Earth-like heliocentric orbit. Nikhef actively supports LISA through both scientific simulations and instrumentation contributions.

The long-term physics analysis strategy of the Nikhef group includes fundamental physics (binary black holes mergers) and physics and cosmology (gravitational waves from binary neutron stars). It seems likely that binary neutron star coalescences will be detected in the next few years. During late inspiral, the tidal field from one star will induce deformation in the other, which affects the orbital motion; this in turn gets imprinted upon the gravitational wave signal and can be measured. How deformable a neutron star will be is set by its equation of state, which is the main open problem in nuclear astrophysics. The observation of multiple binary neutron coalescences will allow us to distinguish between a stiff, intermediate, and soft equation of state. Data analysis in this field is computationally challenging. Nikhef researchers have shown that a waveform-decomposition technique known as Reduced-Order Modelling renders the problem computationally feasible. The same technique will also be needed in tests of general relativity with binary black holes.

Binary coalescences provide a unique opportunity to study relativistic compact objects. The celebrated no-hair theorem states that the geometry of a stationary black hole is determined solely by its mass and spin. This is reflected in the fact that the different vibration modes in the ring-down process have characteristic frequencies and damping times that only depend on mass and spin. The Nikhef group is preparing to put this to the test in upcoming gravitational wave observations. Another exciting possibility that we want to explore in the near future is gravitational wave echoes. Motivated by Hawking's information paradox, it has been argued that black-hole horizons get modified to *firewalls*. If so, the part of the gravitational radiation that is ingoing and would normally be swallowed by the black hole can instead be reflected outward; in practice what one gets is repeated gravitational wave bursts, or echoes, with decreasing amplitude. Even if the characteristic length scale of the corrections is at the Planck scale, the echoes will be loud enough that they can, in principle, be measured.

Apart from binary coalescences, fast-spinning, single neutron stars with small deformations (in the order of 0.1 mm) can also be sources of detectable gravitational waves. These are weak but long-duration signals, allowing for long integration times so that they can be extracted from the data. Detecting such radiation would yield additional information about neutron stars, notably the structure of the crust. The Nikhef group has developed algorithms to detect such signals, and an all-sky search on data from LIGO's first science run is in preparation.

GRAVITATIONAL WAVES GOALS 2017-2022:

- → Commission Advanced Virgo, run jointly with LIGO, and participate in the mid-term upgrade
- → Study gravitational waves from binary black-hole mergers and test black hole physics
- → Discover gravitational waves from neutron star coalescences and measure the neutron star equation of state
- → Investigate the possibility of hosting the Einstein Telescope in the Netherlands

VIRGO detector at Cascina near Pisa

MISSION

To identify and study the particle responsible for dark matter in the universe.

APP → DIRECT SEARCHES FOR DARK MATTER THROUGH XENON

The XENON1T detector has just had its first science run, and data analysis is in progress. Further science runs will follow in the coming years, with continuous detector improvements planned in between the runs.

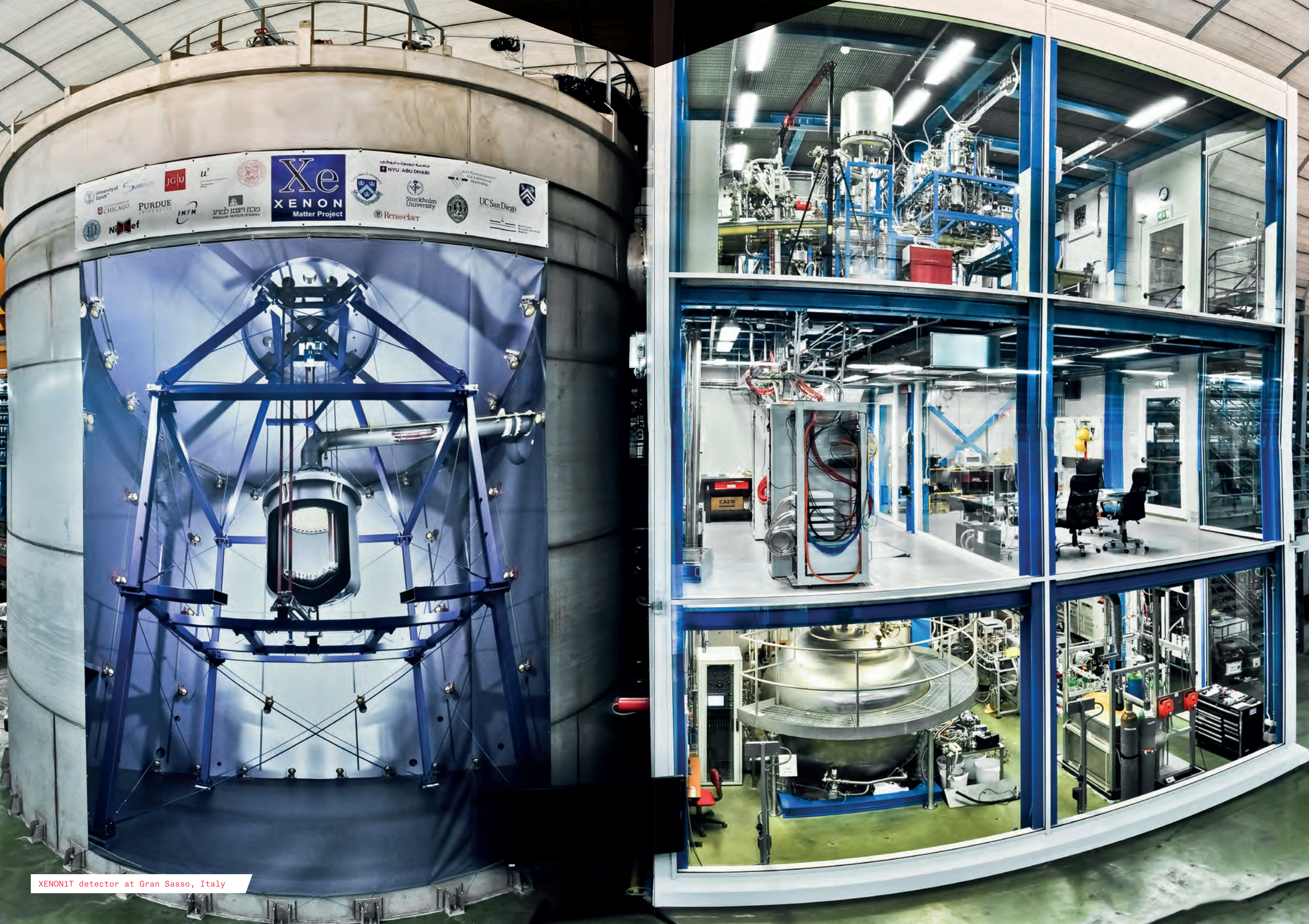
The XENON collaboration is planning on a relatively modest upgrade of the XENON1T setup to the XENONnT phase in 2019. With double the amount of xenon, more light sensors and better control of the radioactive backgrounds, this would improve the sensitivity by about one order of magnitude relative to XENON1T. Most of the XENON1T subsystems have already been designed and built with this upgrade in mind. Experiences with operating XENON1T and its past performance will be important in the further design of XENONnT; the Nikhef group is planning to play an active role in this process. Towards the end of 2016, the collaboration secured a large fraction of the additional xenon and most XENON institution members have also already secured funding for XENONnT.

With XENON1T, the sensitivity on the spin-independent WIMP-nucleon cross section is expected to be approximately 2 x 10^{-47} cm^2 for a WIMP mass of 50 GeV. XENONnT will have an expected sensitivity that is one order of magnitude better. The Nikhef group has also investigated the use of XENONnT for a search for neutrinoless double-beta decay, which indeed appears to be competitive with other detectors.

Further along, we anticipate to build DARWIN, which will be the ultimate direct-detection dark-matter experiment, probing the full experimentally accessible WIMP parameter space using liquid xenon. DARWIN could be built at the Laboratori Nazionali del Gran Sasso (LNGS) once XENONnT is completed in 2024.

DIRECT SEARCHES FOR DARK MATTER GOALS 2017-2022:

- → Search for dark matter signals in the science runs of XENON1T
- → Prepare for the upgrade of XENON1T to XENONnT
- → Investigate the use of XENONnT for the search for neutrinoless double beta decay
- → Prepare for the ultimate direct-detection dark-matter experiment DARWIN



XENON1T detector at Gran Sasso, Italy

MISSION

To investigate the origin and composition of ultra-high energy cosmic rays, their consequences for the understanding of astrophysical objects, and the interaction of these ultra-high-energy particles with the Earth's atmosphere.

APP → STUDYING ULTRA-HIGH-ENERGY COSMIC RAYS USING THE PIERRE AUGER OBSERVATORY

The 3000-km² Pierre Auger Observatory (Auger) has firmly established the sharp drop of the cosmic ray spectrum at the highest energy. The unexpected heavy mass composition towards the end of the spectrum challenges the explanation of this end-point. The sources, acceleration mechanism and composition of ultra-high-energy cosmic rays remain a mystery. Auger measured the proton-proton cross section at a centre-of-mass energy largely exceeding that of CERN's Large Hadron Collider (LHC), the precision and upper energy being limited only by the lack of composition information. In ultra-high-energy hadronic interactions, a surprisingly large number of muons was observed, which cannot be explained by LHC-calibrated models. This problem may be due to a lack of understanding of Standard Model processes, or physics beyond the Standard Model.

Obtaining composition information at the highest energy is crucial, and the first step in this direction involves the upgrade of Auger: AugerPrime. A thin scintillator surface detector (SSD) above the water-Cherenkov stations (acting as surface detector (SD)) will be added to allow to separately measure the number of electrons and muons in air showers. This update will extend the useful lifetime of Auger to 2025 or beyond. Within this programme, we are contributing to the SSD design and we will also produce 10% of the SSD modules in the Netherlands.

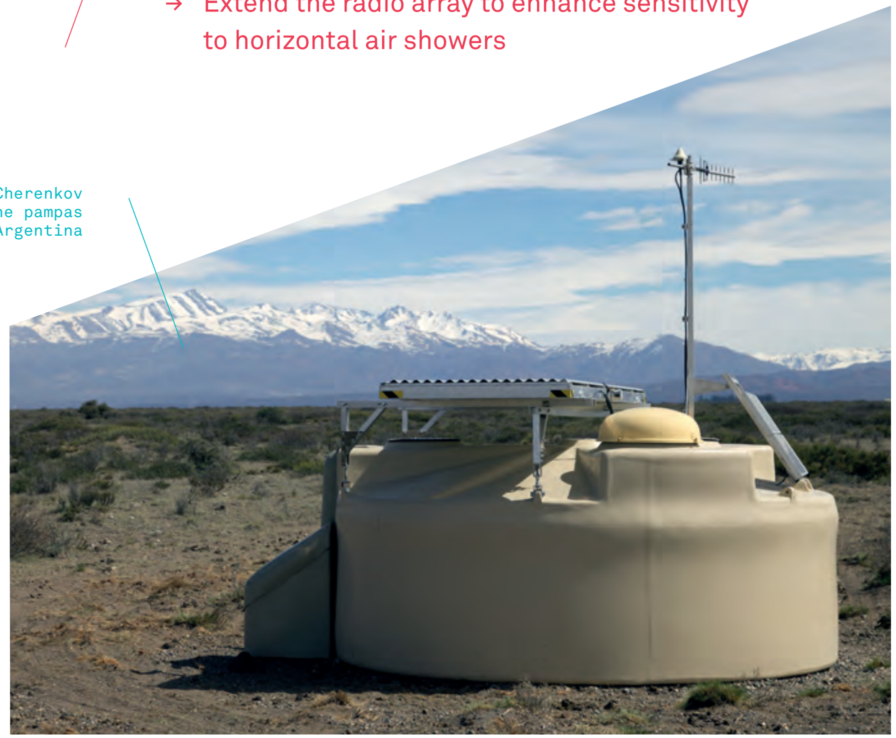
Once the collaboration considers radio detection as part of their baseline, we will submit a proposal to equip all the SD stations in the Pierre Auger Observatory with a radio detector. This will enable calorimetric measurement of the electromagnetic part of horizontal showers, complementing the SD measurement of the muonic component. This large radio detector array will also be sensitive to ultra-high-energy neutrinos, notably tau neutrinos that interact in the atmosphere, Earth crust or Andean mountains to produce a tau lepton that causes a horizontal air shower. In addition, it will establish a precise and absolute energy calibration for the other Auger detectors. Therefore, it provides optimal synergy with the existing detector and its upgrade.

Ideas for further efforts to study ultra-high-energy cosmic rays include a much larger next-generation observatory. Discoveries from the upgrade Auger observatory will be tools for the more advanced high statistics investigations in the proto-collaboration GRAND, a 200.000-km² radio array for ultra-high-energy neutrino, photon and cosmic ray detection.

ULTRA-HIGH-ENERGY COSMIC RAYS GOALS 2017-2022:

- → Complete the AugerPrime upgrade
- → Study muon production in air showers
- → Determine the mass composition of very high-energy cosmic rays
- → Extend the radio array to enhance sensitivity to horizontal air showers

One of 1600 Cherenkov detectors on the pampas of western Argentina



BASE PROGRAMMES

As a final part of the ‘Proven Approaches’ part of the Nikhef strategy (Pillar I), we aim to fully utilise the base programmes at the institute in the areas of theory, detector R&D and computation.

BASE → PHYSICS DATA PROCESSING (PDP)

MISSION

To ensure that the physics reach of Nikhef experiments is never limited by computing. This will be achieved through R&D on scientific computing and collaborative computing, as well as through the operation of and contribution to local, national, and international computing infrastructures for science.

The PDP group’s work falls under four main categories

- → Applied Advanced Computing (AAC) projects target an increased physics reach via research on new algorithms, systems, and software infrastructure; the viability, validity and utility is ultimately tested by application to Nikhef research.
- → Advanced Computing Technologies (ACT) projects aim to define the composition and architecture of our research infrastructures and hardware on a 2-to-5-year horizon.
- → Infrastructure for Collaboration (I4C) topics comprise both infrastructure security (local and world-wide) and collaboration infrastructures. The collaboration infrastructure work has its roots in the LHC-style of global collaboration, but is applicable to many science domains.
- → The available Research Infrastructures (RI) are operated by the PDP group. They are used by Nikhef physicists (the *Stoomboot* computing cluster), our experiment colleagues (LHC Tier-1, VIRGO, XENON) and by other sciences (Dutch National e-Infra structure)

Below we describe our plans for each of these activities

AAC: The Advanced Computing Technology and Research Infrastructures activities provide the platform for continuing development of expertise in Applied Advanced Computing, which is projected to play an increasingly important role in Nikhef experiments. We will search for a new staff physicist in this area, with a focus on high-performance software, algorithms, and parallelization; the model is to solve problems for Nikhef experiments by application of this expertise and coupling to state-of-the-art computing hardware located at Nikhef (and elsewhere).

ACT: The Advanced Computing Technology activity also informs our Research Infrastructures, ensuring that they remain optimal for the actual computing activities of the high-energy physics (and other) communities. At the same time, Advanced Computing Technology is enabled by those same Research Infrastructures. Our scale, expertise and breadth of usage make us an interesting technology partner for the vendors providing the advanced technology. We envision continuing the Advanced Computing Technology line at the current activity level.

I4C: The same holds for the Infrastructure for Collaboration line, which is fully funded from external means due to its importance in building and securing global collaborative research infrastructures (like WLCG and EGI).

RI: We will continue to provide a large Research Infrastructure. The NDPF (Nikhef Data-Processing Facility; our high-throughput platform) will be part of a Tier-1 for LHC, a Tier-like node for XENON and Virgo, and serve Dutch science as a core node of the Dutch National e-Infrastructure. In the short term, we envisage both the NDPF and *Stoomboot*[12] as being virtual clusters provisioned by an underlying cloud facility, giving us much greater flexibility to follow demand and address ‘exotic’ cases. Computing contributions to experiments should count towards e.g. Maintenance and Operation (M&O) contributions in some way. Continuing the Research Infrastructure provisioning to collaborations and national partners is essential to the health of *Stoomboot*, which consists entirely of out-of-service Tier-1 nodes. In the future we will need to augment *Stoomboot* by advanced modern hardware for certain use cases (e.g. simulation of gravitational wave emission).

[12] The Stoomboot (steamboat) cluster is the local batch computing facility at Nikhef. It consists of 3 interactive nodes and a batch cluster with 93 nodes of 8 cores each, running Scientific Linux CERN 6 as operating system.

PHYSICS DATA PROCESSING GOALS 2017-2022:

- Augment PDP scientific staff with expertise in high-performance algorithms and programming
- Transition our Research Infrastructure to a more flexible virtualized system, capable of serving more sciences
- Design (via R&D projects) the Research Infrastructure and Infrastructure for Collaboration components for the HL-LHC era.

Climate-controlled server alley

MISSION

To develop state-of-the-art detector technologies to advance future particle and astroparticle experiments;
To take a leading role implementing these technologies in next-generation experiments via (inter)national partnerships;
To actively pursue collaborations with industrial partners.

BASE → DETECTOR R&D

The detector R&D group maintains links with many experimental programmes through scientific instrumentation, performs basic detector R&D in synergy with Nikhef's engineering departments, and connects with other high-tech research institutes and industry. Successes in this area depend on long-term commitments from Nikhef: the Medipix project has been running for 15 years, GridPix 10 years, and MEMBrane more than five years, for example. They also require substantial resources, and some freedom for independent research by R&D staff members. Instrumentation grant proposals are often only awarded by funding agencies after initial long-term investments by Nikhef. To keep at the forefront of technology, Nikhef needs to invest in enabling technologies like CMOS design, MEMS design and fabrication, advanced optics, digital electronics and signal processing.

Our strategy and planning is focused towards two research tracks and valorisation:

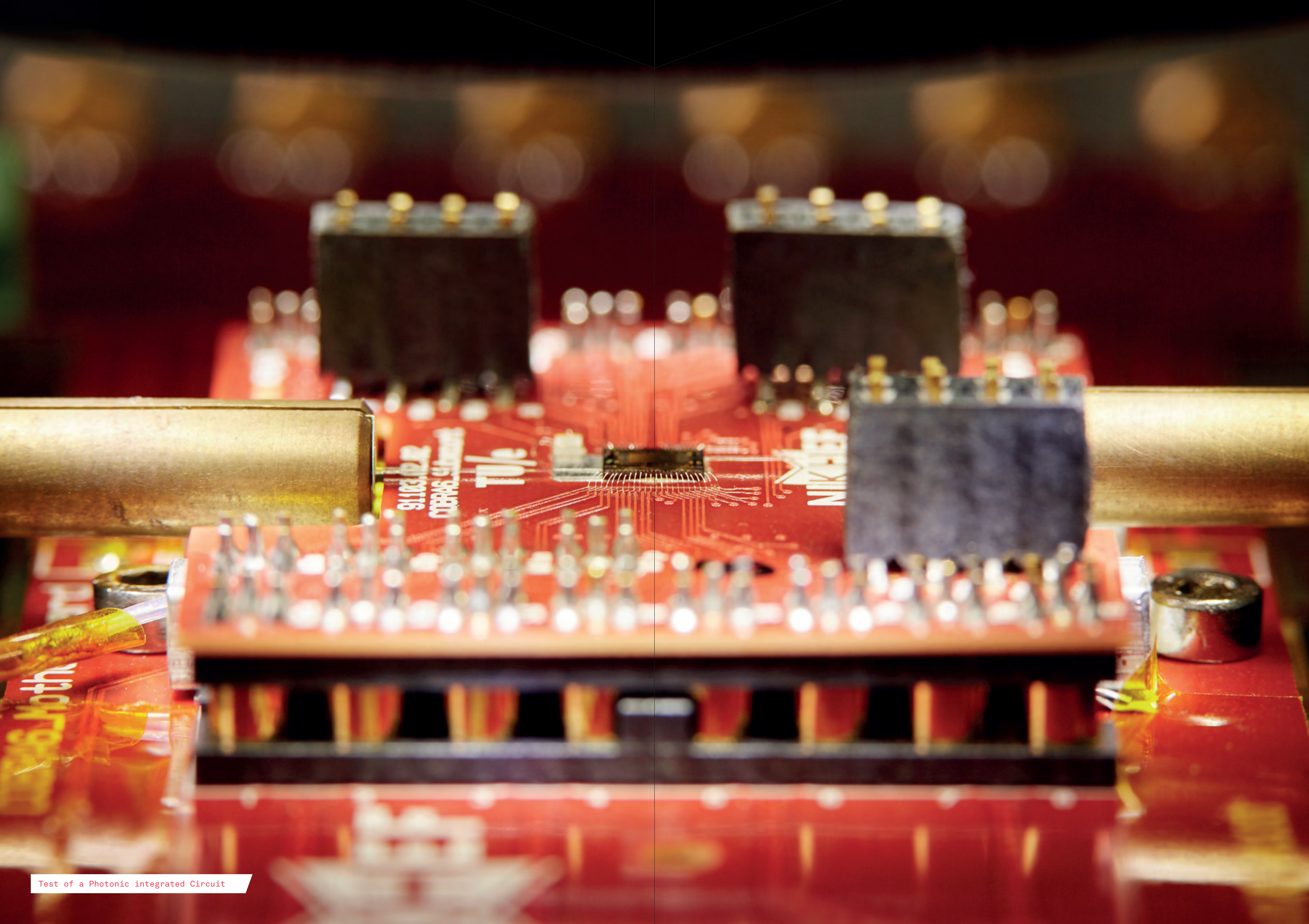
`Instrumentation for gravitational wave detectors:` As part of this track, the development of a sensitive MEMS accelerometer started about five years ago and now involves a granted Topsector proposal to develop a readout ASIC for this device to reach extreme sensitivities. About 10-15 people are involved: physicists, engineers and three PhD students. Other topics concern developments of a phase camera, phase meter, segmented diodes, wave front sensing, seismic sensor arrays, and interferometric techniques. On the longer term, this research is linked to upgrades of Advanced Virgo, LISA, and the Einstein Telescope.

`Smart and fast pixels:` The coming years we will develop new pixel chips, especially pushing for fast picosecond timing and high-speed data links, that allow us to come up with novel detectors. Such a chip can be used e.g. for a photon detector with a stack of transmission membranes. In addition, we are building detector systems for several applications: vertex detectors for LHC experiments, pixel readout of a TPC for a linear collider experiment, mammography, x-ray CT, and muon tomography, for example. Novel sensor materials that come out of advanced (nano-) material research have also generated renewed interest.

`Valorisation:` The detector R&D group initiates and connects projects with industry. Nikhef intends to continue to submit proposals to e.g. the NWO-Open Technology and HTSM Topsectoren programmes to fund enabling technologies. This requires that Nikhef remains a high-tech partner for industry and that it continues to make strategic investments in this area (staff, engineering, and funds). Over the coming years, Nikhef will allocate a sufficient fraction of its resources to instrumentation R&D. There should be sufficient staff with expertise on instrumentation and novel technologies. Nikhef will invest in relations with partners with high-tech fabrication facilities (universities of technology, nano-labs), and/or develop in-house fabrication facilities (e.g., with SRON). This push for state-of-the-art R&D will increase our chances in Topsector programmes, Industrial partnerships, and NWO grants. A threat to this development is the fact that the group size has decreased in the past years, a trend that can be counterbalanced by looking for detector R&D skills in the hiring of new staff.

DETECTOR R&D GOALS 2017-2022:

→ Develop advanced gravitational wave detector instrumentation
→ Develop new smart and fast pixel detectors
→ Invest in relations with high-tech industry



Test of a Photonic integrated Circuit

MISSION

To describe and explain the properties and interactions of subatomic particles; To study theoretical models, such as the Standard Model, for predicting and describing new and existing experimental or observational results, mostly in the framework of quantum field theory; To develop analytical and computational tools for these studies.

BASE → THEORY

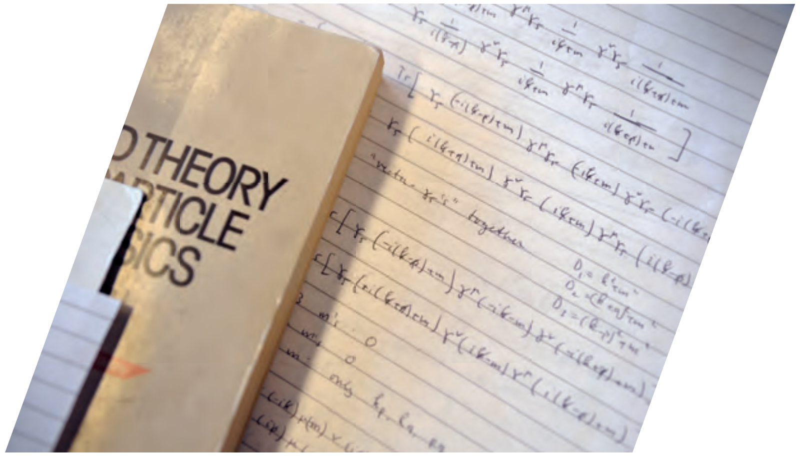
The next years look bright for the theory group. The available funding has enabled us to attract many excellent young scientists, and we look forward to many interesting results. One example is the recent completion of the five-loop Yang-Mills beta function by a largely in-house collaboration. Another sign of quality is that our PhDs and postdocs by-and-large find very good next positions. To maintain this trend, we will continue efforts towards acquiring external funding; we stimulate group members to assist each other with critically reading grant proposals, supplying feedback, and practicing with talks and interviews. It will be difficult to duplicate the success of the past review period, also given the fact that the funding structures in the newly refurbished NWO have not yet been fixed. Another concern is ascertaining a secure future of the algebraic manipulation programme FORM, as the prime developer Vermaseren is reaching his pension. Discussions have taken place with leading groups in Europe, as this is of international interest. As one measure, though by itself not sufficient, a RISE proposal for staff-exchange may be applied for.

In the coming years we will initiate searches for new staff members because two members are retiring. This is essential to stay at the forefront of research and to remain competitive with other top-level institutes.

The role of the theory group as a centre for theoretical particle phenomenology will be strengthened further. The group will have increased interactions with experimental colleagues at the monthly meetings, and stronger links to the GRAPPA institute at the University of Amsterdam.

THEORY PHENOMENOLOGY GOALS 2017-2022:

→ Strengthen the role of Nikhef as a centre for theoretical particle phenomenology
→ Continue to perform state-of-the art calculations relevant to LHC physics and astroparticle physics
→ Consolidate the future of FORM



2B NEW OPPORTUNITIES (PILLAR II)

The second pillar of our strategy for 2017-2022 concerns new opportunities, of which one (measuring the electric dipole moment of the electron) has already been incorporated through a recent grant, and others are in a more exploratory state. We discuss these exciting opportunities below.

MISSION

To perform the most sensitive measurement of the electric dipole moment of the electron.

ELECTRIC DIPOLE MOMENT (EDM) OF THE ELECTRON

Organization

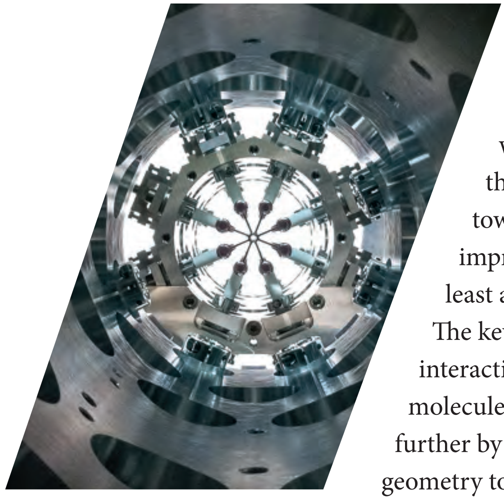
Work in this area is done as part of the FOM (now NWO-I) programme "Physics beyond the Standard Model using cold molecules" led by the University of Groningen with participation of the VU University Amsterdam, that started 1 January 2017. The programme leader is Prof. dr. S. Hoekstra.

Research goals

January 2017 marks the start of the electron-EDM programme, with the beginning of a six-year funded programme by FOM (now NWO-I). The goal of the electron-EDM programme in this period of six years is very clear: we aim to perform the most sensitive measurement of the EDM of the electron. Through this precision experiment, we will put extensions of the Standard Model to a very stringent test, and if a non-zero value of the electron-EDM is found, this would be direct evidence for new physics.

This low-energy, high-precision experiment is a recent addition to the Nikhef portfolio, and presents a wonderful opportunity for significant impact on one of the most pressing puzzles in particle physics: the matter-antimatter asymmetry. This programme represents an approach to particle physics that is complementary to searches for new physics at large-scale facilities such as the LHC. By integrating and supporting this approach to particle physics in its core programme, the Nikhef collaboration has the opportunity to be at the forefront of this development. The experiment will be built at the Van Swinderen Institute in Groningen.

The challenges that have to be overcome during this period of six years are of various natures. Experimentally, this project is very challenging. It requires a combination of novel techniques: a cryogenic molecular beam source, a travelling-wave molecule decelerator with complex high-voltage electronics, transverse cooling of the molecular beam with lasers, and an EDM measurement region that is well shielded from background magnetic fields but with very efficient molecule detection. All these components have to be designed, built, tested and integrated into joint operation. On the theoretical side a number of properties of the BaF molecule have to be accurately calculated, such as the effective internal electric field and the transition strengths for optimal laser cooling. Besides this theory in direct support of the experiment, also open questions regarding the interpretation of a non-zero electron-EDM in terms of extensions of the Standard Model will be investigated.



eEDM: molecule decelerator

To maintain rapid progress on all fronts, we aim to strengthen our electron-EDM team through additional funding where possible. Beyond the running time of the FOM programme, there is a clear path towards a second generation of the experiment, improving on the electron-EDM sensitivity by at least an order of magnitude to ~$0.5 \cdot 10^{-35}$ ecm. The key ingredient of our approach is the long interaction time offered by a slow beam of cold molecules. This interaction time can be increased further by changing the horizontal molecular beam geometry to a vertical 'fountain' arrangement. This step will allow the experiment to probe new physics at energies surpassing those available at the LHC.

ELECTRON-EDM GOALS 2017-2022:

- → Complete the challenging beam and detector set-up
- → Expand the theory needed for the measurement and its interpretation
- → Prepare for a second-generation experiment

NEW INITIATIVES

The following two initiatives are exploratory projects for participation in new experiments. They are not (yet) programmes in the Nikhef organizational structure. The manpower associated with these initiatives at this stage is modest, and typically consists of a few (about 3) staff physicists devoting a fraction of their time (about 20%) to these projects, one or two full-time PhD students, and limited technical support. Depending on international developments, further interest from Nikhef staff, and funding opportunities, these projects may grow in the coming years.

NEW → (PROTO)DUNE

Nikhef plans to expand its activities in neutrino physics with activities in the Deep Underground Neutrino Experiment (DUNE) after 2025. Activities on protoDUNE, to test the infrastructure, will already be carried out in the coming years.

DUNE is designed as a leading-edge experiment for neutrino science and proton decay studies. It will take place at FermiLab and at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, with beam lines comprising the world's highest-intensity neutrino beam, and the infrastructure necessary to support massive, cryogenic *far detectors* (liquid-argon TPCs) installed deep underground, 1300 km downstream from the neutrino source. The physics programme of DUNE intends to measure the CP-violating phase δ_{CP} in the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix to a 10-degrees accuracy, to establish the hierarchy of neutrino mass states (normal or inverted) to >5 standard deviations, and to accurately determine the mixing angle θ_{23} and its octant. It will also search for anomalous tau neutrino appearance, non-standard interactions, sterile neutrinos, and proton decay, and if a supernova explodes within our galaxy within the right time window, DUNE will observe hundreds of neutrinos from the explosion. A *near detector* at FermiLab will allow electroweak physics research using a very large data sample.

In principle, DUNE relies on proven technology, but at a whole new scale. As part of the CERN neutrino platform, protoDUNE at CERN aims to test this technology, and will be subjected to SPS test beam in 2018.
The ambition of Nikhef is to improve event reconstruction of neutrino events, starting with protoDUNE. Nikhef has proposed to use the FELIX readout system, as developed for ATLAS. A proof-of-principle setup is being prepared for protoDUNE.

NEW → LEPCOL

Nikhef anticipates participation in an experiment at the International Linear Collider (ILC- Japan; the next global e^+e^- collider; see also the section on 'future colliders' below), in particular the ILD experiment. The physics case for a high-energy e^+e^- collider rests on four pillars: studies of the Higgs boson with unprecedented accuracy, precision electroweak physics, studies of the top quark, and searches for new phenomena beyond the Standard Model, complementary to those at the LHC.

Within the LEPCOL initiative, Nikhef prepares in first instance for high-accuracy data analysis of the Higgs particle decaying into tau leptons. A measurement of the coupling of the Higgs particle to the heaviest lepton is of great interest, and the reconstruction of tau leptons requires high-accuracy tracking and vertexing. A pixelised readout of a TPC could offer excellent tracking performance, and Nikhef has started a hardware R&D project in this area, building on expertise with *GridPix* detectors in the Nikhef R&D group.

NEW INITIATIVES GOALS 2017-2022:

- → Prepare an extended neutrino physics programme by participating in the protoDUNE programme. The DUNE programme itself starts at FermiLab around 2025.
- → Prepare for hardware and analysis contributions for an experiment at the next linear e^+e^- collider

NEW RESEARCH THEMES

With the consolidation of the experimental portfolio, the fertilization of the science drivers between the experiments will obtain further attention. Currently, the scientific programmes of Nikhef function rather independently and opportunities to mutually enforce and create synergy are sometimes missed. For the next period, Nikhef will initiate a number of in-house 'research themes' to increase the scientific cohesion of the research programmes. Scientific staff members will be associated to each of these themes to initiate discussions and prepare scientific output with support from a modest number of dedicated PhD students and postdocs.

NEW RESEARCH THEMES GOALS 2017-2022:

- → Initiate the theme 'Neutrino Physics' to increase the cohesion between the Nikhef KM3NeT, DUNE and Auger activities.
- → Initiate the theme 'Dark Matter' to increase the cohesion between ATLAS, LHCb, XENON1T/nT and KM3NeT programme activities.
- → Initiate the theme "Global fits to HEP data" to investigate the cohesion of various Standard Model measurements like the old LEP results and recent ATLAS, LHCb and XENON results.

OPPORTUNITIES BEYOND 2022

The future of Nikhef is linked to that of CERN; the extremely successful international accelerator laboratory with an ambitious 'post-LHC' future. We find it worth noticing that, in view of the challenges in particle physics, Nikhef supports a closer collaboration between CERN and the astroparticle physics (APP) community. With the vigour of CERN, constructive partnerships will have an immensely positive impact on a number of crucial APP experiments.

Nikhef will substantiate its longer-term future in both accelerator physics and astrophysics. We emphasize the High-Luminosity LHC, future colliders and the Einstein Telescope in the next section.

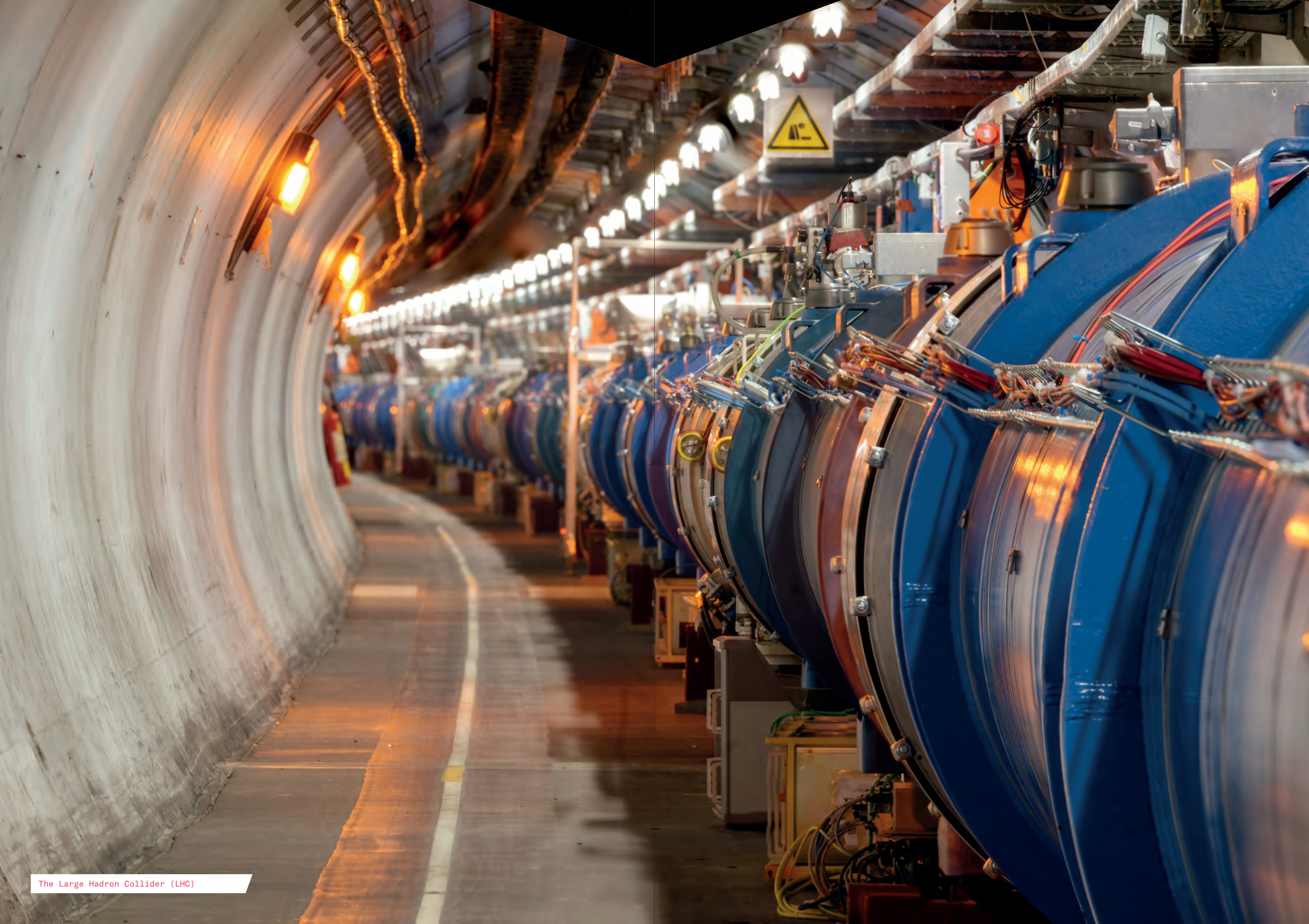
OPPORTUNITIES → HIGH-LUMINOSITY LHC

The physics programme of the HL-LHC extends as far as 2035. During this period, the full physics potential will be exploited, i.e. most measurement uncertainties will then be dominated by systematics or limited by the beam energy. The HL-LHC has the potential to find new particles, symmetries or subtle deviations from the Standard Model predictions. The impact of such discoveries is huge and corresponds to a paradigm shift of particle physics. In particular, the full data set of HL-LHC is needed to observe the enigmatic Higgs self-coupling.

Nikhef will participate in the ATLAS phase-2 upgrade and HL-LHC running. The precise amount of Nikhef's involvement in the HL-LHC upgrades and running of the LHCb and ALICE experiments is still open and will be decided at a later stage, based on physics opportunities.

GOALS OF HL-LHC BEYOND 2022:

- → Utilize the rich ATLAS, LHCb and ALICE physics potential of the HL-LHC
- → Realize the main long-term goals of ATLAS, such as a high-precision characterization of the Higgs boson, and in particular, the observation of the Higgs self-coupling



The Large Hadron Collider (LHC)

OPPORTUNITIES → FUTURE COLLIDERS

In order to elucidate the fundamental physics questions and puzzles in the 21st century, there are several future collider projects that are being proposed and researched by the particle physics community. The physics reach of the future collider projects is in general complementary to the physics programme that is foreseen for the High-Luminosity LHC and other facilities. The main quest of e.g. an electron-positron collider is the study of the couplings and properties of the Higgs particle with unprecedented precision. In addition, very accurate measurements will be performed in the top-quark and electro-weak sector and BSM physics searches will be performed in areas that are difficult to uncover at the LHC.

Several future collider projects are being discussed worldwide. Some of these are considered to be mature and achievable with currently available collider technologies, others are still in an R&D stage. Here, we summarize briefly the most important future collider projects.

An important worldwide project is the International Linear Collider (ILC), in which Nikhef has started initial studies (see LEPCOL above). The project proposes an electron-positron collider with energies up to 500/1000 GeV in a 31/50 km tunnel in Kitakami (Japan). Both the accelerator and the detectors have been studied in detail and are in a mature technical state. The project is currently waiting for approval by the Japanese government and could provide collisions in 2035. In China, a Circular Electron Positron Collider (CEPC) in a 54-100 km tunnel is under study; at a later stage, a Super Proton-Proton Collider (SPPC) could be placed in this tunnel. The CEPC option could start by or before 2035 reaching energies up to 240-250 GeV, allowing detailed studies of the Higgs particle.

CERN has two projects under study with starting dates beyond or far beyond 2035. The first is the Future Circular Collider (FCC), a high-energy version of the current LHC proton-proton collider in the LEP-LHC tunnel. FCC projects are based on a new 90-100-km-long tunnel located in the Geneva area. In that tunnel, first, an electron-positron collider with energies up to 350 GeV will be constructed and operated (FCC-ee) and, at a later stage, a proton-proton collider reaching an energy of 100 TeV (FCC-pp). Finally, the Cern LInear Collider (CLIC) project aims to realise a linear electron-positron collider reaching energies of 380 GeV, 1.5 and 3 TeV in a 11-50-km tunnel running parallel to the lake of Geneva. The collider technology is still under development. However, discussions are ongoing to start with a first phase using mature, existing technologies.

There is wide support at Nikhef to join a future collider project - such as the ILC - in the not-too-distant future when matured and approved. Further, Nikhef strongly supports the further development of the R&D for a high-energy electron-positron collider, the FCC-ee, and the proton version, the FCC-pp. In the scenario that new symmetries or particles are observed at the LHC, Nikhef supports the construction of a new collider to investigate the new particles. In the absence of beyond the Standard Model physics signals, Nikhef supports the construction of the infrastructure that is able to measure all properties of the Higgs particle to a next increased level of accuracy, i.e. an electron-positron collider. The costs of these bold projects are gigantic. Nikhef will remain critical concerning the balance between costs and physics gains of the projects.

The discovery of the Higgs particle at the LHC was a major breakthrough that showed us the spectacular physics in a very early phase of our universe. What exactly occurred at its birth, within the first fraction of a nanosecond can be studied and explored at the next generation of colliders. It is truly a unique opportunity for mankind to realise such a facility.

FUTURE ACCELERATOR VISION BEYOND 2022:

- → Support an ambitious future accelerator programme at CERN.
- → Contribute to detector construction and science exploitation in the case that Japan builds the ILC or China the CECP.
- → Exploit the unique opportunity opened by the next generation of accelerators at CERN (CLIC, FCC-ee and FCC-pp) to explore the physics processes of the extremely early universe.

EINSTEIN TELESCOPE

The Einstein Telescope (ET) is the European initiative to build a worldwide network of third-generation ground-based interferometers, aiming to start taking data around 2030. The ET is a research facility in which multiple interferometers are placed that will be developed in the next decades (foreseen until about 2060). The first interferometers already gain a factor 10 in sensitivity compared to the design sensitivities of Advanced Virgo, leading to a 1000-fold increase in the number of observations. With the ET, gravitational wave research enters a new domain.

The science programme of the ET is large and diverse. It impacts astronomy, astrophysics, cosmology and fundamental physics and brings the exploitation of these science-domains close together. The ET is primarily designed as broadband detector with a mostly excellent sensitivity in the 2-10^4 Hz frequency domain. A number of important classes of potential sources for astrophysics lie in this domain that can be traced for long periods of time, such that optical radio and other telescopes can benefit from the signal to make multi-messenger analysis possible. In addition, dynamic astronomical sources like gamma-ray bursts can be observed by the ET. Further, the ET will be able to observe yet unobserved, new and imaginative sources.

In a few years' time, the ET site will be selected. Nikhef has the ambition to prepare a realistic bid for hosting the ET in the Netherlands around 2020. All relevant stakeholders, both national and international, will be brought together to examine the reality of this plan. The support of Belgium and Germany as well as the astronomy communities is crucial. Further scientific and political support, regional development (attracting high-tech industries, etc.), optimizing socio-economic impact and establishing a national profile will be crucial to realize the ET in the Netherlands.

Hosting the ET in the Netherlands will have impact in areas beyond particle physics. It will boost Dutch science in general and increase its international reputation. The region will benefit from innovation, industry and technical challenges. The realization of ET in the Netherlands will also have a large impact on Nikhef. Besides an increase of the mission budget, a sizeable fraction of the astroparticle physics efforts of Nikhef is foreseen to migrate toward gravitational wave research to enlarge the Dutch scientific contribution to the ET. The Netherlands will benefit from the presence of this new worldwide infrastructure.

In the scenario that the ET will not be located in the Netherlands, the ambition of Nikhef remains to actively participate in this endeavour, wherever it is hosted.

EINSTEIN TELESCOPE GOALS 2017-2022 AND BEYOND:

- → Explore the opportunity to host the ET in the Netherlands in order to present a realistic bid around 2020
- → Connect all relevant national and international parties to optimize the Dutch bid
- → Prepare and develop a local small-scale interferometer as technology demonstrator

Presentation of the Einstein Telescope project to Dutch Prime Minister Mark Rutte at the Hannover Messe 2016

2C BEYOND SCIENTIFIC GOALS (PILLAR III)

Next we describe the goals for Nikhef beyond the realm of doing science. They concern its international position, knowledge & technology transfer, outreach, education and renovation of the Nikhef building.

THE ROLE OF THE NIKHEF PARTNERSHIP

The Nikhef partnership of five Dutch universities is seminal for the Netherlands to achieve first-class research in the international 'Big Science' area. In the Nikhef model, the institute serves as a bridge between international infrastructures, like those at CERN, and research at Dutch universities. Reversely, leadership and talent from the universities are brought into Nikhef to remain viable.

The power of Nikhef lies in its complete infrastructure to perform particle physics at the highest level. The contributions to international experiments are focused, strong, and with the dedication "to make things happen". Numerous problems, anticipated or not, in the area of instrumentation, software, computing and analysis tools have been solved in the past by Nikhef. Very often these problems were not even part of the Nikhef responsibilities, but if possible, we will step in to help. This makes Nikhef a sought-after partner with an excellent international reputation.

NIKHEF PARTNERSHIP GOALS 2017-2022:

- → Remain a strong institute with an excellent international reputation and leadership positions
- → Remain open for collaboration with other universities such as Leiden, Maastricht, Delft and Twente.

CONNECTION TO SOCIETY

In order to strengthen our connection to society, we aim to keep informing the general public about the outcomes of R&D at Nikhef and to transfer knowledge and technological innovations to stakeholders.

CONNECTION TO SOCIETY → KNOWLEDGE AND TECHNOLOGY TRANSFER

CERN's Director-General Fabiola Gianotti at the industrial Holland@CERN exhibition in May 2016

Over the past years, Nikhef has seen an increase in its knowledge and technology transfer activities. In particular, we point to the emergence of an environment in which the creation of technology spin-offs is greatly enabled. Assuming the current national *Topsector* policy will remain in place for a while, Nikhef intends to maintain and where possible increase its current level of valorisation efforts.

The appointment in 2016 of a fulltime Coordinator Industrial Contacts fits this intention. The coordinator has the tasks to detect opportunities and stimulate cooperation with industry in common research projects or simply in contract research. As a very appealing example, we are exploring the possibility to realize by 2020 a small – about 20 meters arm length – laser interferometer as a public – private (VDL, Shell and other industries) collaboration project, strongly supported by the Province of Limburg, to develop several of the key technologies planned for Einstein Telescope.

Regarding our spin-off policy, we have learned that a role as shareholder –although appearing attractive at first sight– can be cumbersome. Therefore, Nikhef will be a bit more reticent to take such a position in the future.

We will also continue our policy regarding *patenting*. We will preferably patent knowhow or technology only if there are concrete indications that a third party is interested in using it. As many of our knowhow is developed in cooperation with our university partners, we will also continue our policy to commonly share the Intellectual Property.

KNOWLEDGE AND TECHNOLOGY TRANSFER GOALS 2017- 2022:

- → Increase valorisation efforts
- → Continue spin-off policy
- → Continue patent policy

CONNECTION TO SOCIETY →
OUTREACH AND COMMUNICATIONS

MISSION

To foster appreciation and support for Nikhef and (astro) particle physics in particular, and science in general;
To convey the importance of fundamental research fulfilling the intrinsic desire of mankind to explore;
To position fundamental research as a driving force for knowledge increase, technological innovation, and scientific education.

The two major scientific discoveries of recent years (the Higgs particle, announced in 2012, and gravitational waves, announced in 2016) have had a huge impact not only on the scientific community but also on societal target groups. Nikhef organized a rich palette of outreach and communications activities. All this has resulted in strong and continuous interest in and support for Nikhef's research.

The challenge for outreach and communications is to maintain (and possibly further increase) the current level of interest and support. To this end, we aim to increase the understanding amongst the target groups for the process of science and fundamental research in which projects are often long-term and progress is often in the form of small advances. Nikhef's communications strategy envisages to communicate about all of Nikhef's diverse scientific programmes in the fields of particle and astroparticle physics including experiment and theory, computing, detector R&D, and instrumentation. Nikhef also sees this as an opportunity to showcase that in the wake of this fundamental research there are ample technological innovations that can also be applied in other fields, as well as many other societal benefits.

Key messages in Nikhef outreach

- → The discoveries of the past years open up new windows and lead us on a journey in understanding the universe in terms of its elementary particles and fields.
- → Nikhef is a leading, renowned institute in the field of particle and astroparticle physics, with a strong reputation both nationally and internationally.
- → Nikhef uniquely combines exciting science, technology and skills.
- → Nikhef's activities benefit society by contributing to driving technological innovation, to inspiring and engaging people and to training future generations.

The main target audiences Nikhef strives to address are the general public, the media, decision makers and funding agencies, industry, the scientific community and the educational system. To appeal to these groups and to raise awareness and engagement with Nikhef's research, Nikhef aims to offer a wide range of tailor-made activities, conveying a consistent message, which is presented with a modern visual identity.

OUTREACH AND COMMUNICATION GOALS 2017-2022:

- → Increase the visibility of Nikhef and its continuing strong reputation
- → Create content and stories to consistently convey the key messages to the different target groups
- → Develop a new, modern visual identity for Nikhef
- → Stimulate an interactive, two-way communication both in person and 'digitally' (website, social media)
- → Assist the Nikhef employees in their outreach activities as ambassadors for the institute

Dutch national radio interview at CERN

International Masterclass on Particle Physics for secondary-school students at Nikhef

EDUCATION

Nikhef puts great effort into inspiring and training the next generation of young scientists. From various programmes for school children and their teachers, to Bachelor's, Master's and PhD programmes, Nikhef considers education an integral part of its activities to benefit society.

Nikhef fosters young talents arriving from universities in the Netherlands and abroad, particularly through participation in the Master's programmes of the universities and PhD projects at Nikhef. The Research School for Subatomic Physics (OSAF) plays a central role in the education programme.

During the past years, the prospects for PhD students to remain in academia were perceived to be difficult. For a young generation of students, it is often not clear what the prospects for a position in academia are. While Nikhef cannot make any guarantees to individuals for obtaining a tenured position, it intends to increase the transparency for a career path inside and outside of academia.

EDUCATION GOALS 2017 → 2022

- → Enthuse young people and attract students into science and technology subjects.
- → Foster young talents in the OSAF PhD programme and prepare for a career path.

RENOVATION

The oldest part of the Nikhef buildings in Amsterdam is almost 37 years old; the more recent part is 21 years old. In 2015-2016, Nikhef developed a plan for renovating the building. At an estimated total cost of 20 to 25 M€, this renovation would address necessary updates and replacements of various technical installations and make the building reliable, affordable and future-proof for at least another 20 years, complying with the latest standards regarding (environmental) sustainability. It also includes an upgrade of the building interiors, to enable the users perform their high-quality research and detector instrumentation efforts, adapted to modern insights in using workspaces, meeting rooms, etc.

RENOVATION PLANS 2017-2022:

- → Nikhef deems a renovation of its building to be essential for its future and for continuing to be an attractive environment for new generations of researchers.

FINANCIAL SCENARIO 2017→ 2022

03

The current status of funding for Nikhef in the coming five years is represented in Table 1. The budget items are categorized along the same lines as explained in our evaluation document:

- → Programmes: funding usually for a longer term (6-8 years), covering the scientific exploitation of our experiments with primarily temporary scientific staff (postdocs, PhD students);
- → Mission budget: the base funding for the institute, covering all fixed costs;
- → NWO-I projects: small projects funded under the former FOM-projects granting scheme; this type of funding will be replaced by funding instruments under the new NWO Science Domain scheme;
- → Additional funding: any other source of funding and income: NWO funding, EU funding, funding from contract research and the datacentre;

TABLE 01 **Nikhef 'secured' funding**

NWO-institute only (in M€)	2017	2018	2019	2020	2021	2022
Programmes	1,9	2,1	1,9	1,8	1,7	0,4
Mission budget	14,0	14,0	14,0	14,0	14,0	14,0
NWO-I projects	0,8	0,5	0,3	0,2	-	-
Additional funding, of which	13,3	7,5	7,9	6,6	6,0	4,7
→ NWO (including investment grants)	5,9	1,9	2,5	1,4	1,0	0,3
→ EU	1,3	0,7	0,4	0,4	0,2	
→ Other (including turnover data centre)	6,1	5,0	5,0	4,8	4,8	4,4
Total	**30,0**	**24,1**	**24,1**	**22,6**	**21,7**	**19,1**

3A CURRENT MISSION BUDGET AND PROGRAMME FUNDING

The dissolution of FOM and the restructuring of NWO have changed the funding landscape for Nikhef considerably. Per 2017, Nikhef avails over a *mission budget* of 14 M€, which is substantially more than in the previous period (then around 12 M€). However, this does not represent an actual budget increase for Nikhef in total, but only a shift in *labelling* of funds: part of what FOM labelled as *strategic programmes* (mainly for PhD students and postdocs) has been added to the mission budget. The difference is that this mission budget, including this previous strategic programmatic compartment, is supposed to be a 'guaranteed' funding stream, the amount of which is subject to the mission evaluation, taking place every six years.

However, the remaining part of the former FOM programme funding will gradually decrease in the coming years, conforming the original funding scheme. The largest fraction of this concerns funding for the scientific exploitation of LHC experiments (PhD students and postdocs). The year 2022 shows only funding for the most recently acquired FOM programme (eEDM).

One of the largest uncertainties that Nikhef faces in the near future is therefore whether the new *NWO Science Domain* will open funding opportunities for large and long term (6 – 8 year) programmatic activities, such as for the scientific exploitation of the LHC experiments.

FUNDING CHALLENGE 2017 → 2022

→ Obtain programmatic funding within the new NWO Science Domain (increasing to almost 2 M€ annually) to maintain the current level of funding.

3B ADDITIONAL FUNDING

In our 2011-2016 strategy, we aimed at obtaining an additional funding at a level of 2 M€ annually, mainly in the form of NWO and EU project funding (excluding investment grants). We have reached this objective and even surpassed it, also due to an unexpected large success in the ERC Advanced Grant competition. For the 2017-2022 period we aim for an even higher target: 3 M€ annually, from all available funding sources. We will continue to help staff preparing grant applications in all possible ways needed, such as internal review mechanisms, external text editors (science writers), interview and presentation training, etc.

NWO GRAVITATION

In the next strategic period Nikhef will also aim for a so called 'NWO Gravitation grant': a special NWO funding instrument for programmes of 10-year duration, targeted at nation-wide consortia of the highest scientific quality in the Netherlands. This proposal will be centred around the national astroparticle physics agenda. The aim is to acquire around 20 M€ of funding for temporary scientific staff and tenure track positions plus some moderate running costs (travel) and investments.

NET INCOME OF THE DATA CENTRE

Due to the still increasing market perspective Nikhef has very concrete plans to extend its data centre to accommodate new customers, who wish to connect to our site. The investment cost is estimated at 4 M€, which is expected to be earned back by the additional generated turnover in about 7 years. The current net income of the data centre will therefore remain intact and we aim to increase this even to over 2 M€ annually, both by further reducing operating cost (energy efficiency measures) and by (slightly) raising the housing and connection fees.

INVESTMENTS

Following the ambitions sketched in this research strategy, Nikhef will aim for several investment funding opportunities in the coming period:

National Roadmap of Large-Scale Research Infrastructures

For the Dutch share of the investments in KM3NeT 2.0, Nikhef has recently (1 June 2017) submitted a proposal in the call of the Dutch National Roadmap for Large-Scale Research Infrastructures. The total estimated cost of the facility is 125 M€. The requested contribution from NWO is 12,7 M€.

The earliest in the 2019 call of the National Roadmap Nikhef aims to submit a proposal for instrumentation for the Einstein Telescope. The actual request is very much dependent on the feasibility of an ET situated in the Netherlands.

Also in 2019 and dependent on developments regarding the funding of the national e-infrastructure (computing, data, etc.) Nikhef might need to submit a funding proposal for another five years of Tier-1 investments. As it looks now it may be advisable to team up with other data-intensive sciences, in particular astronomy (SKA), since the size and character of the data processing challenges are comparable.

NWO-groot grant scheme

The aim of the NWO-groot (large) grant scheme is to stimulate investments in very advanced scientific equipment or innovative data collections of national or international scope. It offers opportunities for proposals of several million euro (usually between 2 and 4 M€). In the upcoming calls of 2017 and 2019, Nikhef aims to submit proposals for the following two research initiatives: one for Auger – Radio detection (preferably as a joint Nikhef-astronomy proposal) and one for instrumentation needed for interferometric gravitational wave detection. This last initiative will be focused on the crucial upcoming upgrades of Advanced Virgo (similar upgrades are planned for Advanced LIGO in the USA), while at the same time it will also be used to optimally position the Netherlands for a bid in around 2020 to host the third generation gravitational waves Einstein Telescope project.

Renovation costs

Renovating the Nikhef building will require an investment estimated between 20 and 25 M€. Nikhef can't cover this from its mission budget – the major share should be funded by our funding agency, as has been the case with renovations or investments in new buildings of our sister institutes. Unfortunately, until now there has been no concrete prospect of obtaining this funding. A dialogue with the new NWO Board has been initiated. In anticipation of this highly needed renovation and to cover at least the most urgent issues regarding the building maintenance (such as timely replacement of critical installations), Nikhef plans to reserve in the order of 0,5 M€ annually from its mission budget to cover part of the planned renovation cost. It should be noted that combining the renovation ambition with the planned expansion of the Nikhef data centre may render a net saving of 1 M€ in total expenditure due to construction synergies.

The table below summarizes the (ambitious) funding targets for the coming period.

TABLE 02 **Nikhef funding targets for 2017-2022**

(Research) activity	Year(s)	Funding target
LHC physics, astroparticle physics	2018-2022	Obtain long term (6 – 8 year) programme funding from NWO Science Domain for postdocs and PhD students, increasing to 2 M€ annually in 2022
Astroparticle physics	2018-2022	Obtain 'NWO Gravitation' grant: ca. 20 M€ for 10 years to strengthen the Dutch astroparticle physics activities with tenure track positions, temporary scientific staff and moderate investments
All research activities	2018-2022	Obtain additional funding (from NWO, EU, etc.) for PhD students, postdocs and other personnel (working e.g. on engineering efforts) of 3 M€ annually
Data centre	2017-2022	Increase net income above 2 M€ annually
KM3NeT 2.0	2018	Obtain investment of 12,7 M€ (National Roadmap)

CONTINUE →

(Research) activity	Year(s)	Funding target
Auger radio detection	2018	Obtain investment of 3 M€ (NWO Large)
Gravitational Wave research	2018-2020	Obtain investment of 4 M€ for Virgo upgrade and ET instrumentation (NWO Large)
LHC experiments – Tier 1	2020	Obtain investment of 3 M€ for Tier-1 to run for another 5 years
Einstein Telescope	2020	Obtain investment, amount to be determined, depending on site selection
Renovation of building	2017-2022	Obtain funding for the renovation (total sum estimated at 20-25 M€); Combine with expansion of data centre (estimated synergy saving: 1 M€).

MISSION BUDGET INCREASE

The ambitions to obtain funding for the Nikhef strategy are high. This will strain the current mission budget considerably, as most funding calls require a significant amount of co-funding. On top of this, Nikhef needs to reserve funds from its mission budget for the renovation of the building. We therefore make the case for a sizable increase of our mission budget, with at least 1 M€ annually. This is a similar plea as stated in our previous strategy (2011), strongly supported by the 2011 evaluation panel, which however did not materialize.

Such a mission budget increase will be used by Nikhef for strengthening the staffing in our astroparticle physics activities, in particular in the Gravitational Waves group and also in our Detector R&D group, since we expect a huge appeal on expertise for developing the extremely advanced instrumentation required for gravitational wave detection.

If the preparations for a Dutch bid for the Einstein Telescope location are successful, Nikhef foresees the need for an even larger increase in the mission budget, particularly for strengthening the technical and engineering support.

COLOPHON

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Nikhef participates in experiments at the Large Hadron Collider at CERN, notably ATLAS, LHCb and ALICE. Astroparticle physics activities at Nikhef are fourfold: the ANTARES and KM3NeT neutrino telescope projects in the Mediterranean Sea; the Pierre Auger Observatory for cosmic rays, located in Argentina; gravitational-wave detection via the Virgo interferometer in Italy, the direct search for Dark Matter with the XENON detector in the Gran Sasso underground laboratory in Italy. The low-energy eEDM experiment is located at the University of Groningen. Detector R&D, design and construction take place at the laboratory located at Amsterdam Science Park as well as at the participating universities. Data analyses make extensive use of large-scale computing at the Tier-1 grid facility operated jointly by Nikhef and SURFsara. The Nikhef theory group has its own research programme while being in close contact with the experimental groups