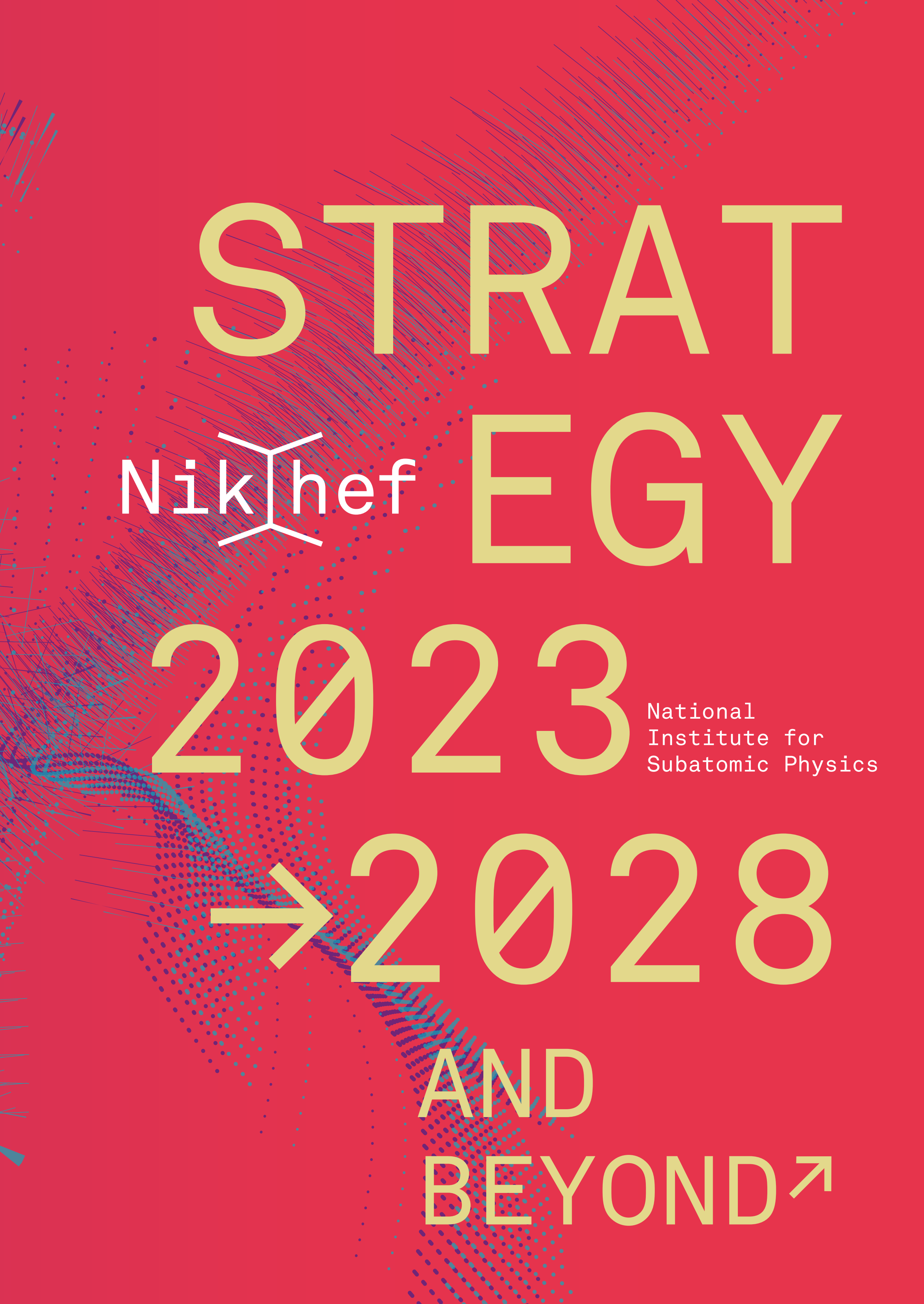

STRATEGY 2023 → 2028 AND BEYOND↗

Nikhef

National
Institute for
Subatomic Physics

NIKHEF STRATEGY
2023 → 2028 AND BEYOND

NIKHEF MISSION STATEMENT

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. Research at Nikhef relies on the development of innovative technologies. The transfer of knowledge and technology to third parties, i.e. industry, society and the general public, is an integral part of Nikhef's mission.

CON NECTING THE LARGE AND THE SMALL

STRATEGY AT A GLANCE

As a national partnership, Nikhef is determined to make a difference in international research in particle and astroparticle physics. Over the period 2023-2028, this ambition leads to the following concrete actions, grouped in four themes.

Theme 1. **Expanding knowledge**

Our main research effort is aimed at further exploring our understanding of the universe in terms of elementary particles and forces, through the interpretation of data and by confronting the results with theory and vice versa. We aim to:

- → Develop new theoretical models utilising high-precision data of the experimental programmes;
- → Search for new (Beyond the Standard Model) phenomena in data from the LHC experiments ATLAS, LHCb and ALICE, and the eEDM experiment in Groningen;
- → Exploit the discovery potential of the 'multi-messenger' astroparticle physics experiments KM3NeT, Auger and Virgo, and the XENONnT experiment;
- → Develop innovative data-reconstruction and -analysis strategies using artificial intelligence, machine learnign and quantum-computing technologies throughout Nikhef's scientific portfolio.

Theme 2. **Providing technologies**

Much of Nikhef's effort is put into upgrading and exploiting the current experiments and building upcoming experiments. The technology departments at Nikhef are essential to make this happen. We aim to:

- → Contribute to the upgrades of the LHC experiments scheduled to be installed during LHC's Long Shutdown 3 (LS3, 2025-2028), in particular the major upgrade for ATLAS;
- → Continue the digital optical module (DOM) assembly, integration and deployment for KM3NeT;
- → Complete the first phase of the ETpathfinder R&D laboratory in Maastricht and contribute to the crucial interventions/upgrades required to make Virgo competitive with the LIGO facilities in the USA;
- → Perform maintenance of hardware in the (astro)particle physics experiments

Theme 3. **Preparing the future**

Nikhef is constantly innovating towards new technologies and designs of new facilities and projects to explore new scientific challenges and opportunities in the years to come. We aim to:

- → Continue the R&D on '4D fast timing' to be able to implement this technology for the upgrades of the LHC experiments in the 2030s;
- → Prepare the technical design of the Einstein Telescope and investigate if a realistic bid to host the Einstein Telescope in the Euregion Meuse-Rhine can be made;
- → Intensify participation in XLZD, DUNE and a next-generation UHECR.

Theme 4. **Fostering healthy partnerships**

Nikhef strives to be a vibrant, diverse and inclusive community in the (inter)national field of (astro)particle physics, offering a safe work environment and investing in people's talents and expertise. We aim to:

- → Expand on the diversion and inclusion agenda, and pursue (gender) balance in leadership positions;
- → Work toward climate neutrality in 2030, and pursue our sustainability agenda for travel and the primary process;
- → Strengthen links to industry and other research institutes;
- → Exploit the (new) possibilities of the new Nikhef building to foster talent and outreach activities.

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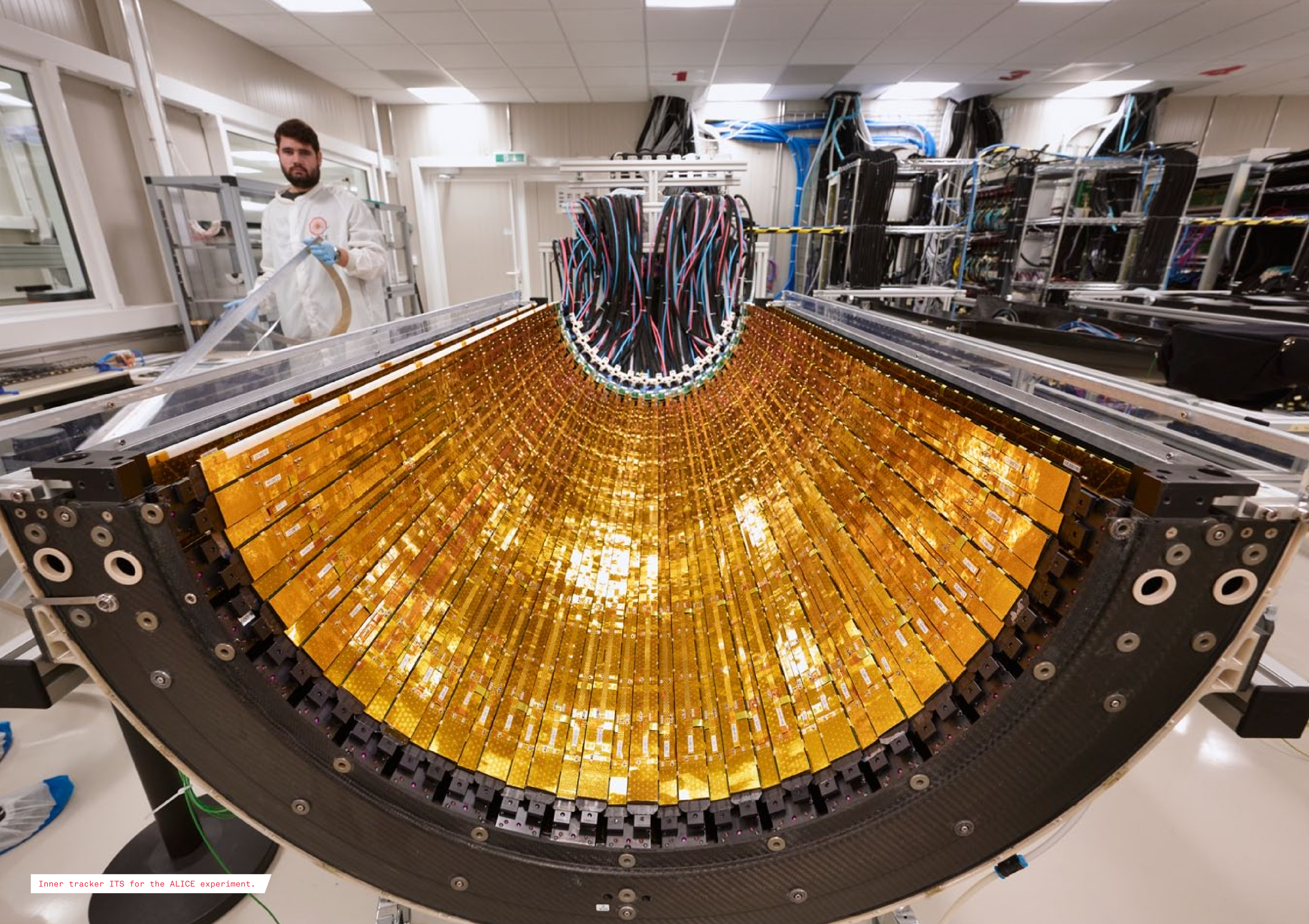
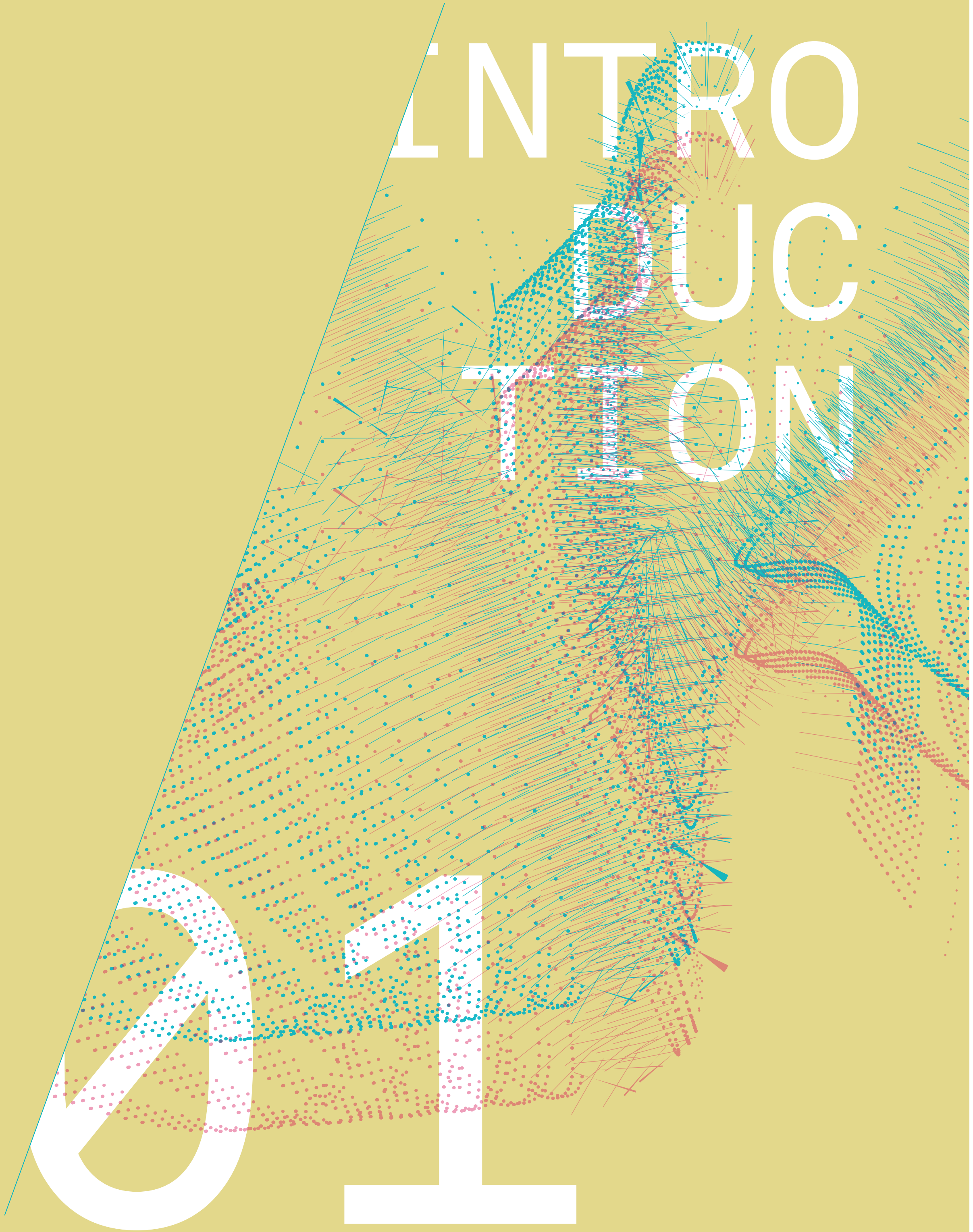


Inner tracker ITS for the ALICE experiment.

01 INTRODUCTION



EXCITING TIMES

Particle and astroparticle physics are going through exciting times. Not so long ago, the Higgs particle was discovered, implying the existence of an invisible field which permeates everything around us and thereby gives mass to all atomic matter in the universe. Gravitational waves, another recent discovery in our field, give us not only direct access to black holes, but also shed light on gravity as a fundamental force, the last of all known forces to be unified. While studying our universe, the nature of space-time itself has become a topic of research.

Some questions continue to challenge us. Where did all the antimatter go after the Big Bang? What are the properties of the neutrinos and why are their masses so small? Do they even get their mass through the Higgs mechanism? Why are there exactly three generations of elementary particles? How can we explain the remaining 80% of the mass of the universe, whimsically referred to as dark matter? Where are the particle accelerators in the universe that continually bombard the Earth with protons, nuclei and other forms of radiation?

The Standard Model of particle physics, and the theory of general relativity, comprises all our current understandings in the field. But we know that there must be deeper reasons for all these questions to exist. With more precise measurements and better theoretical understanding, we realise each time that nature is more complex and wonderful. The Standard Model must correspondingly and perhaps perpetually evolve unless a whole new theory emerges. In the Netherlands, Nikhef constitutes the partnership through which answers are sought to such questions. We contribute to the construction and operation of world-class research infrastructures, which require state-of-the-art technologies to be developed and unprecedented volumes of data to be scrutinised. In turn, this pushes theory to new limits.

Nikhef played an important and visible role in many of the breakthroughs mentioned above, with scientists in leading positions and instrumentation in the hearts of the detectors involved. We are motivated and prepared to further unravel the mysteries of our universe in terms of the smallest building blocks of nature.

Stan Bentvelsen,
summer 2023

READING GUIDE

This report contains the strategy for the coming six-year period, 2023-2028, prefaced by a section with information about Nikhef.

The strategy for 2023-2028 lays out the main directions and objectives of the ongoing and planned research activities. In essence it details the visions, plans, needs and ambitions of the research institute and the partnership for the next six years.

This strategy report forms, together with the self-evaluation report, input for the six-yearly evaluation of the institute. The self-evaluation and strategy are structured according to the Strategy Evaluation Protocol (SEP), used in the Netherlands to evaluate research entities.[1] An international committee has been set up and will visit Nikhef for an independent evaluation. We will use their evaluation as further guidance.

Impression of the new entrance for the Nikhef building in Amsterdam.

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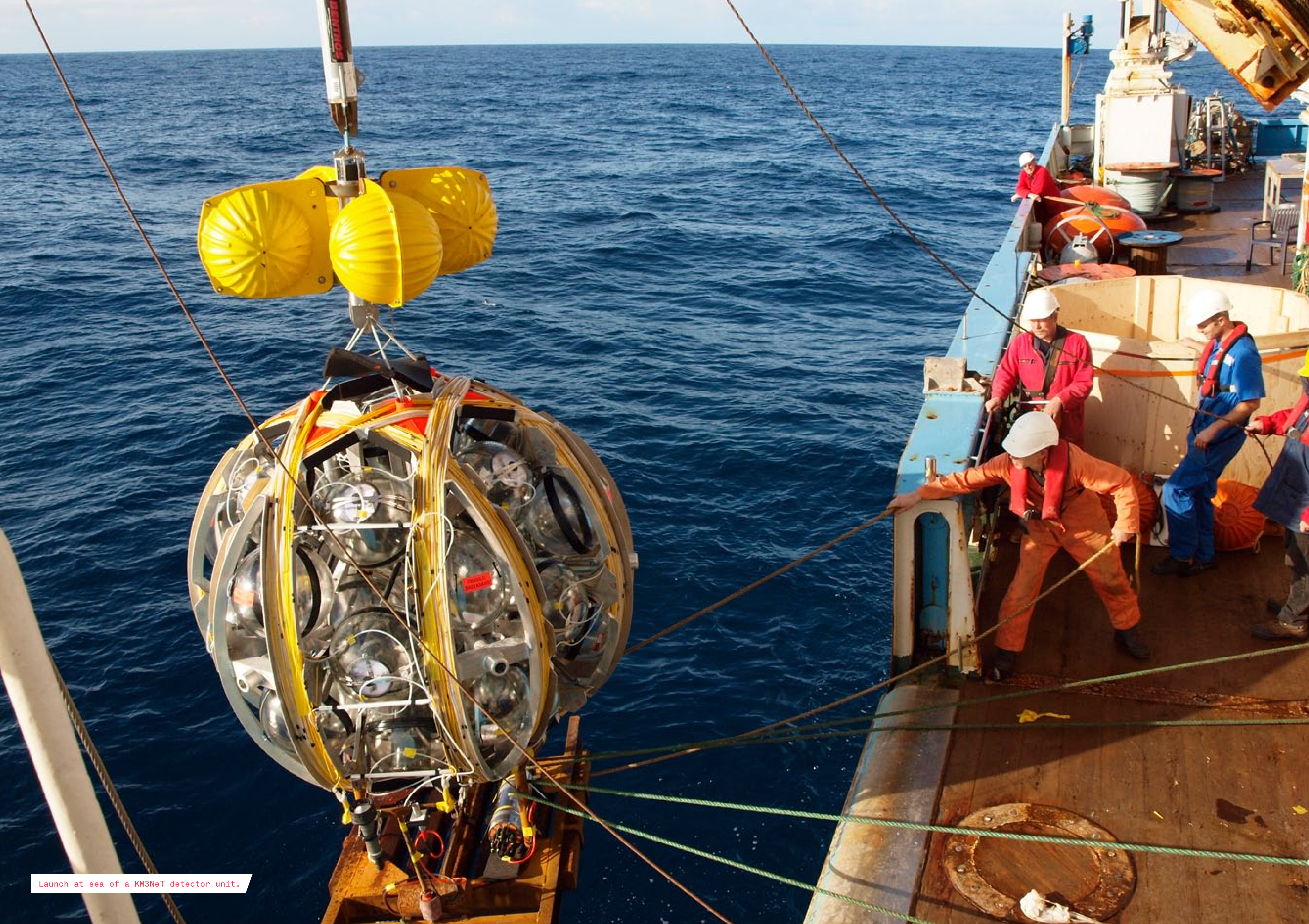
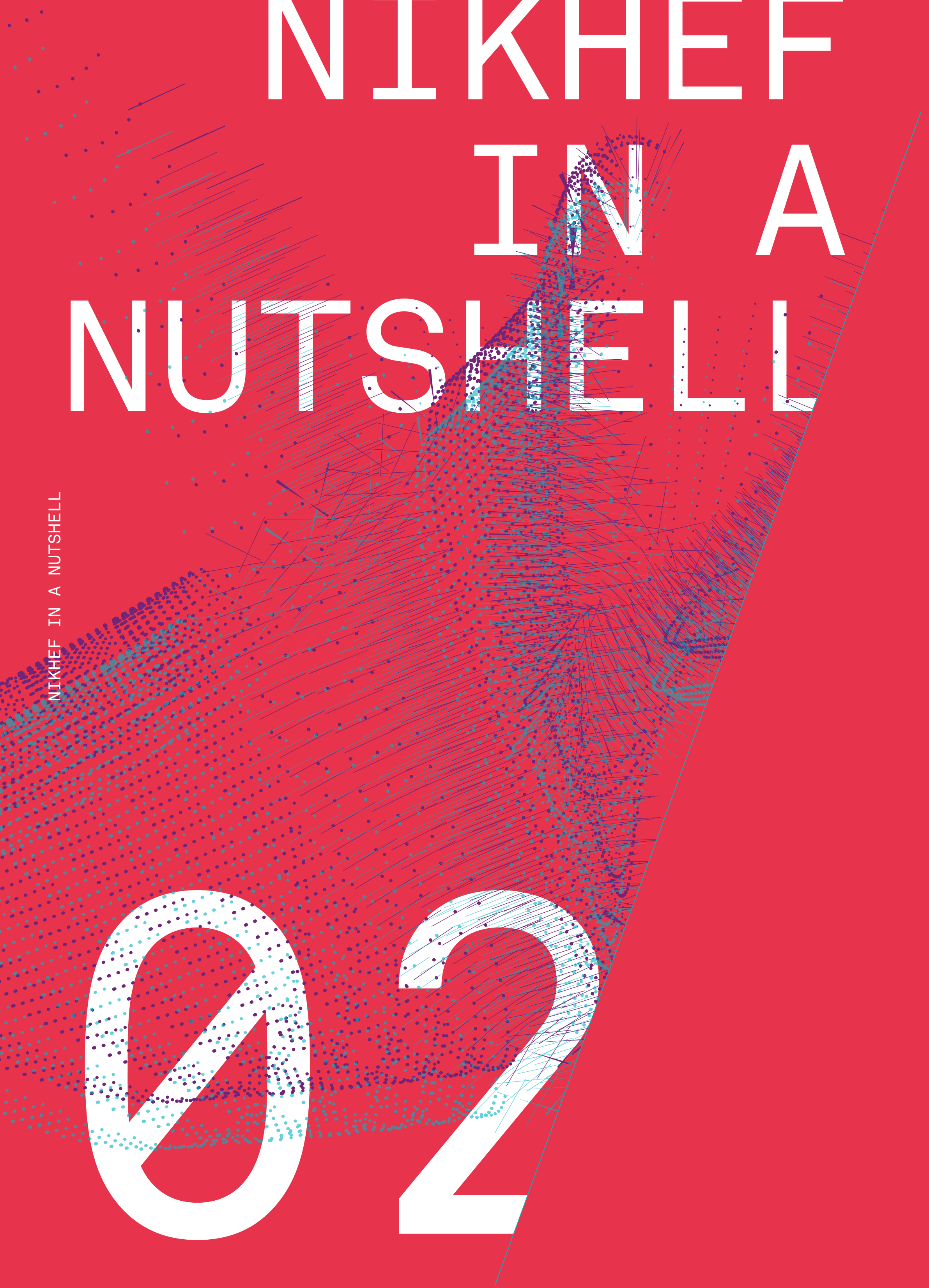
[1] See https://www.universiteitenvannederland.nl/files/documenten/Domeinen/Onderzoek/SEP_2021-2027.pdf



Launch at sea of a KM3NeT detector unit.

NIKHEF IN A NUTSHELL



02

Nikhef is the national institute for (astro)particle physics in the Netherlands. As such, it is both a research institute under the umbrella of the Foundation for Dutch Scientific Research Institutes (NWO-I, part of the Dutch Research Council NWO) and a partnership with six Dutch universities. Nikhef not only coordinates and leads the Dutch activities in the field, it also facilitates access to large international consortia and research infrastructures around the world. In this section we discuss in more detail the mission of Nikhef, its partnership, embedding, history, science drivers, research portfolio and ambitions for the future. In addition, relevant external developments and societal trends are discussed, setting the stage for the Nikhef strategy.

2.1 MISSION STATEMENT

The mission of 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: accelerator-based particle physics (studying interactions in particle-collision processes at particle accelerators, in particular at CERN) and 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 transfer of knowledge and technology to third parties, i.e. industry, society and the general public, is an integral part of Nikhef's mission.

2.2 RESEARCH PROGRAMMES AND TECHNICAL GROUPS

The Nikhef research portfolio can be roughly divided in three main areas, namely: (accelerator-based) particle physics, astroparticle physics and enabling programmes:

- Accelerator-based particle physics
  - Higgs, Standard Model and Beyond Standard Model physics: ATLAS
  - Flavour physics: LHCb
  - Heavy-ion physics: ALICE
  - Electron Electric Dipole Moment: eEDM
- Astroparticle physics
  - Neutrino physics: KM3NeT & DUNE
  - Dark matter: XENONnT & XLZD
  - Ultrahigh-energy cosmic rays: Pierre Auger observatory
  - Gravitational waves: Virgo, Einstein Telescope & LISA
- Enabling programmes
  - Theory
  - Detector R&D
  - Physics data processing (PDP)

Nikhef strives to maintain a healthy science-motivated balance between particle physics and astroparticle physics. For this strategy period, this implies that the sum of our activities at CERN will roughly be equal to the sum of our other activities. In addition, new developments emerging outside the above areas are closely monitored for possible new research opportunities.

Nikhef also houses three technical departments with suitable facilities:

- Computer technology
- Electronics technology
- Mechanical technology

2.3 \ SCIENCE DRIVERS

Foremost, we want to find the answers to the most important questions in (astro)particle physics, doing this we also have the ambition to be a key player in the field. Our ambitions cover the design, construction and operation of (astro)particle instrumentation as well as the processing, analysis and interpretation of science data.

In this section we give an overview of the science drivers for the ongoing and future research projects within the Nikhef research portfolio. These science drivers constitute the foundation for the Nikhef 2023-2028 strategy, which will be discussed in the next chapter. The enabling programmes and technical groups play an essential role in the realisation of this strategy.

Precision Higgs physics	Except for its mass, all properties of the Higgs particle are precisely predicted by the Standard Model. Accurate experimental checks of these properties are seminal in the search for 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 astrophysics.
Discovery of new particles and symmetries	Any discovery of new underlying symmetries or new particles will provide a paradigm shift in 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 unknown. Oscillations between the various flavours of neutrinos may unlock the mystery of matter versus antimatter of our universe. Point sources provide the key to the origin of high-energy cosmic particles.
Quark-gluon plasma	To understand the multi-body dynamics of the quarks and gluons of the strong interaction, and in particular how they give rise to the properties of the high-temperature phase of QCD, the quark-gluon plasma (QGP).
Matter - antimatter differences	The origin of the subtle differences between matter and antimatter particles is unknown.
Cosmic messengers	To understand the origin and acceleration mechanism for ultrahigh-energy cosmic rays, charged particles of various kinds, neutrinos and photons, cosmic messengers are studied.
Electron properties	An accurate measurement of the electric dipole moment of the electron provides, through subtle quantum effects, a sensitive probe for physics beyond the Standard Model.

2.4 \ FOCUS AND MASS: BUILDING A COHERENT PORTFOLIO

Experimental particle and astroparticle physics involves engaging in international ‘big science’, by participating in numerous experiments and opportunities worldwide. To ensure that the Netherlands is able to make a significant impact in this field, Nikhef focuses on a limited number of key experiments that together form a coherent portfolio. Focus and mass are keywords here. The choice of Nikhef to participate in a new project is based on its scientific relevance, related to our mission, and its potential for Nikhef to make a large impact. In practice this involves an organic process that may take several years. We describe these considerations in a certain order, but in practice iterative discussions take place.

A new experiment may continue an ongoing research line or broaden our portfolio. In the first case we assess how the new experiment corresponds to a logical progression from an ongoing research line. For example, the XLZD project is a logical successor of XENONnT for the direct search of dark matter. Here, expertise and know-how are valuable a-priori assets. An example of the second case is the addition of the new high-precision low-energy physics line with the eEDM experiment. This new and highly sensitive instrument to search for physics beyond the Standard Model was initiated by RUG, and is a strong case for broadening our portfolio.

Nikhef prioritises experiments that require building the infrastructure as well as exploiting and interpreting the data. Within our field, these complementary expertise areas go hand in hand, and ensure a powerful optimisation of the design and exploitation of the hardware.

In all these considerations, it remains crucial to maintain the right focus and avoid spreading ourselves too thin. A very important consideration is the availability of personnel and expertise in the technical departments. On the other hand, with too much focus we run the risk of putting too many eggs in one basket. Our portfolio should not become too rigid and we consider a certain degree of diversification. An illustrative example is Nikhef entering the field of gravitational wave physics, which at the time (around 2007) brought much discussion as it involved physics other than the familiar particle physics. Since then, this line of research has proven to be an important enrichment of our portfolio.

Participation in new projects should be in line with our national and international strategies and adhere to agreements with astronomers regarding specific roles and responsibilities. Evidently, we take feedback of our Scientific Advisory Committee (SAC) into account, and it is worth mentioning that year after year, the SAC has acknowledged our well-balanced portfolio and highlighted the significance of our focused approach, which enables us to make a difference in the field. For example, in 2023, the SAC report said "*The SAC confirms that Nikhef's long-term research strategy is coherently synchronised with the internationally developed strategies in particle and astroparticle physics.*"

Additionally, some of our researchers are involved in smaller endeavours, closely related to our core portfolio. These activities increase the probability of finding new avenues for scientific discoveries but are not (yet) part of our portfolio.

2.5 \ PARTNERSHIP

Nikhef is a partnership of the Dutch Research Council NWO (via its foundation NWO-I) and six Dutch universities, namely the **University of Amsterdam (UvA)**, **VU Amsterdam (VU)**, **Utrecht University (UU)**, **Radboud University (RU)**, **University of Groningen (RUG)** and **Maastricht University (UM)**. The Nikhef institute is located at Science Park, Amsterdam. In this section, the Nikhef partnership is referred to as "Nikhef" unless otherwise stated.

One of the key roles of Nikhef is to unify and federate all Dutch activities in the field. Its strength lies in a fruitful cooperation between the partners and an optimal selection of the joint research programmes. To this end, Nikhef organises regular meetings between all researchers to evaluate ongoing activities and explore new areas of research. Furthermore, the Nikhef institute houses departments for theory, computing, R&D and supporting technologies. It provides added value, continuity and critical mass. Nikhef also constitutes a hub for the partners of international consortia and research infrastructures. Thus, the whole of the partnership is greater than the sum of its parts.

At present, the Nikhef community consists of about 200 permanent staff (scientific, technical and support) and about 170 temporary staff (PhD candidates and postdocs). Of the permanent scientific staff, around 60 persons are employed by the partner universities and 30 persons by NWO-I, i.e. a ratio of 2:1. The success of Nikhef and the quality of the staff is evidenced by its leading roles in international collaborations and involvement in the management of large projects, and by elected positions (such as spokesperson and physics coordinator) and nominations "à titre personnel" (such as (co-)chair and member of various committees).

Most of the research programmes have their home-base at the Nikhef institute. For these, Nikhef provides the working environment and facilities for the staff, postdocs and PhD candidates. The PhD candidates and postdocs can equally well be employed by NWO-I or one of the universities. Usually, but not necessarily, a science programme is led by a university-employed (full) professor, providing them recognition in the partnership as well as in the home university. The technical and engineering activities are concentrated at the Nikhef institute but universities have a fair and sometimes outstanding share. Appointing and evaluating staff, whether at a university or at the Nikhef institute, follows the standard procedures within NWO-I and the universities. Nowadays, these aspects rightfully receive extra attention (see e.g. “Recognition and Rewards” and diversity initiatives at NWO-I and universities). The integral scientific programme is led by the Nikhef director. The Nikhef board, in which NWO-I and the university partners are represented, formally approves the programme, including the budgets. Before that, the scientific programme is reviewed by the Scientific Advisory Committee (SAC), which is composed of independent experts in the field.

Due to this tight integration of the Nikhef institute and the university partners, previous mission evaluations of Nikhef (in 2000, 2007, 2011 and 2017) have always been from the perspective of the Nikhef *partnership*. The current self-evaluation and strategy continue this tradition.

TABLE 1 **Involvement in research programmes**

Involvement of the Nikhef institute and universities in the various Nikhef programmes (P designates a programme leader role, D a deputy programme leader role and S scientific staff).

	NWO-I	UvA	VU	UU	RUG	RU	UM
Theory	P,S	S	S	S	S	S	S
ATLAS	P,S	D,S				P,S	
LHCb	P,S		D,S		S		P,S
ALICE	S			P,D,S			
Neutrino	P,S	D,S					
Dark Matter		P,S					
Cosmic rays	S					P,S	
eEDM		S	S		P,S		
GW	S	S	D,S	D,S	S	S	P,S
R&D	P,S	S					
PDP	P,S						

Repeatedly, the Nikhef partnership and its underlying model have been praised by external committees. For example, the Restricted European Committee for Future Accelerators (RECFA), a body that regularly visits each country in Europe and provides recommendations, has stated so at its last visit to the Netherlands in 2017. Also, the Permanent Committee of National Institutes (PCNI) has praised the Nikhef model for the positioning of partners in the national landscape.

UPDATES IN THE NIKHEF PARTNERSHIP

The Nikhef partnership was established in 1975. Until 2016, the partnership consisted of the FOM institute (now restructured into an NWO-I institute) and four universities, namely: University of Amsterdam (UvA), VU Amsterdam (VU), Radboud University (RU) and Utrecht University (UU). On 19 February 2016, the University of Groningen (RUG) joined the Nikhef partnership with the Van Swinderen Institute. RUG’s eEDM experiment is now part of the Nikhef physics programme. In 2019, Maastricht University (UM) also joined the partnership, bringing the total of Nikhef university partners to six. UM houses the ETpathfinder and is involved in the LHCb programme and in quantum computing.

The core of the Nikhef partnership is worded in the first consideration of the Partnership Agreement: “The importance of the research discipline of (astro)particle physics requires that the experimental research, carried out in the various organisations, is coordinated nationally in one common programme.”

National and international coordination and long-term commitments in ‘big science’ are the keywords. While at the start of the partnership more than 40 years ago, national activities in high-energy physics and nuclear physics were brought together (hence, the Dutch acronym ‘NIKHEF’), Nikhef now comprises (almost) all activities in the Netherlands in experimental (accelerator-based) particle physics and astroparticle physics.

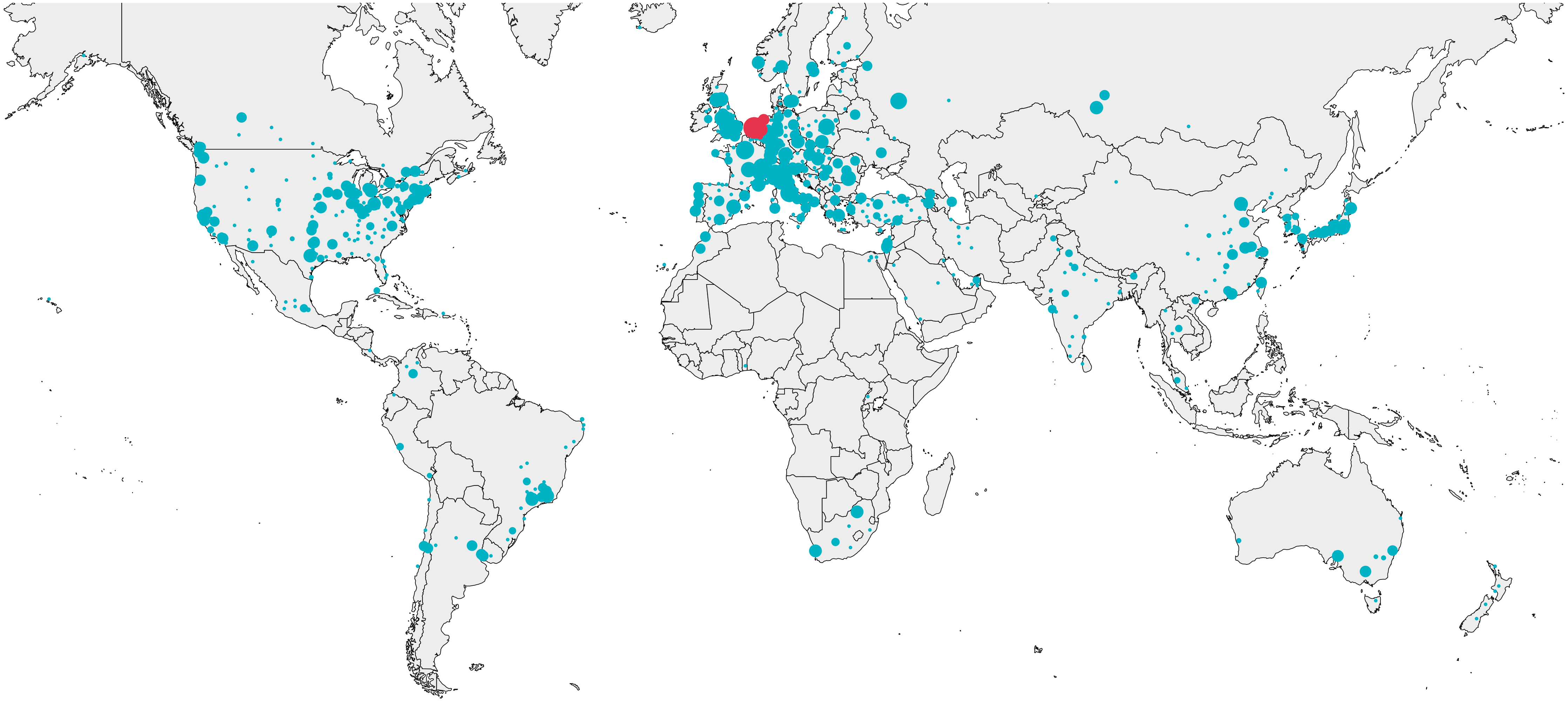
2.6 \ EXTERNAL PARTNERS AND CONSORTIA

Nikhef has a number of external partners of which CERN in Geneva is the most important. In the coming years and decades, CERN will continue to play a pivotal role for Nikhef. A large part of this strategic plan therefore involves experiments at the Large Hadron Collider (LHC), namely ATLAS, LHCb and ALICE. In addition, Nikhef has long-term agreements with various international consortia in astroparticle physics. These consortia have been set up to build and operate (large) research infrastructures located in Italy (Virgo, KM3NeT-ARCA and XENONnT), France (KM3NeT-ORCA) and Argentina (Pierre Auger Observatory). Nationally, the University of Groningen houses the eEDM facility while the ETpathfinder is being constructed in Maastricht. Further external partnerships of Nikhef cover activities in detector R&D, computing infrastructure and theory. Locally, partnerships typically involve community exchanges and visitor programmes which contribute to a lively atmosphere.

Currently, a large new community is being formed in Europe around the Einstein Telescope (ET) project, more specifically in the Euregion Meuse-Rhine (EMR) around Maastricht. Together with national and international partners, mostly in Belgium and Germany, we have the ambition to host the ET in this region (suitability of the geological underground is a necessity, and studies of the geology in the region are underway). With a grant from the National Growth Fund, Nikhef has established connections with the ministries of OCW and EZK, the Province of Limburg and the LIOF company. If all necessary criteria have been fulfilled, including geology and financial commitments, we plan to prepare a bid book to host the Einstein Telescope in the EMR. Further interactions in this endeavour are with institutes in Flanders, Wallonia and Germany, as well as other (Dutch) industrial partners. Museums are involved as well (e.g. Museum Boerhaave and Discovery Museum).

Nikhef has also close ties with the University of Twente, Delft University of Technology and Leiden University in the form of knowledge

FIGURE 1 **Worldwide collaboration partners of Nikhef in scientific publications (source: CWTS).**



exchange, special professorship appointments, lecturing and BSc and MSc student projects. Various schools for higher professional education (*hoger beroepsonderwijs*, hbo) are connected via student internships at Nikhef. Last but not least, the institute has numerous outreach connections with primary and secondary schools and societal clubs and associations.

Nikhef is a longstanding member of the European Committee for Future Accelerators (ECFA) and fully committed to the European Strategy for Particle Physics, which was updated in 2020. Likewise, for its astroparticle physics activities, Nikhef is a member of the Astroparticle Physics European Consortium (APPEC) and adheres to its 2016 roadmap, which had a mid-term update in 2021. The Dutch astroparticle physics community and the astronomy community are jointly organised through the Astroparticle Strategic Forum (AppS), for which the Committee for Astroparticles in the Netherlands (CAN) provides strategic advice. The Nikhef strategy is in line with the advice of the CAN.

Further national collaborations are established with the centre of excellence for Gravitation and Astroparticle Physics (GRAPPA) at the University of Amsterdam, the Institute for Mathematics, Astrophysics and Particle Physics (IMAPP) at Radboud University, the institute for Gravitational Waves and Subatomic Physics (GRASP) at Utrecht University, and the Fundamentals of the Universe (FotU) research theme at the University of Groningen. For the Laser Interferometer Space Antenna (LISA), connections with the space research organisation SRON have been established. Nikhef is well positioned in the national e-Infrastructure as coordinated by SURF with which we closely cooperate. We also work together with ASTRON in data-intensive computing. Further collaborations exist with TNO and NIOZ within the KM3NeT programme. We have close contacts with a large number of companies and have set up industrial research collaborations via the start-up companies Innoseis Sensor Technologies and Amsterdam Scientific Instruments.

In the end, the largest and most important partner of Nikhef is society. Science cannot exist without it. In this context, it is worth noting that fundamental research and technical innovation resonate with the general public. This is demonstrated by Nikhef’s involvement in a large number of outreach activities, radio and television items, newspaper articles and books.

2.7 EXTERNAL DEVELOPMENTS AND SOCIETAL TRENDS

While societal trends and developments in terms of sustainability, openness, diversity and inclusion, knowledge and technology transfer, and outreach are discussed elsewhere, here we limit ourselves to three key observations.

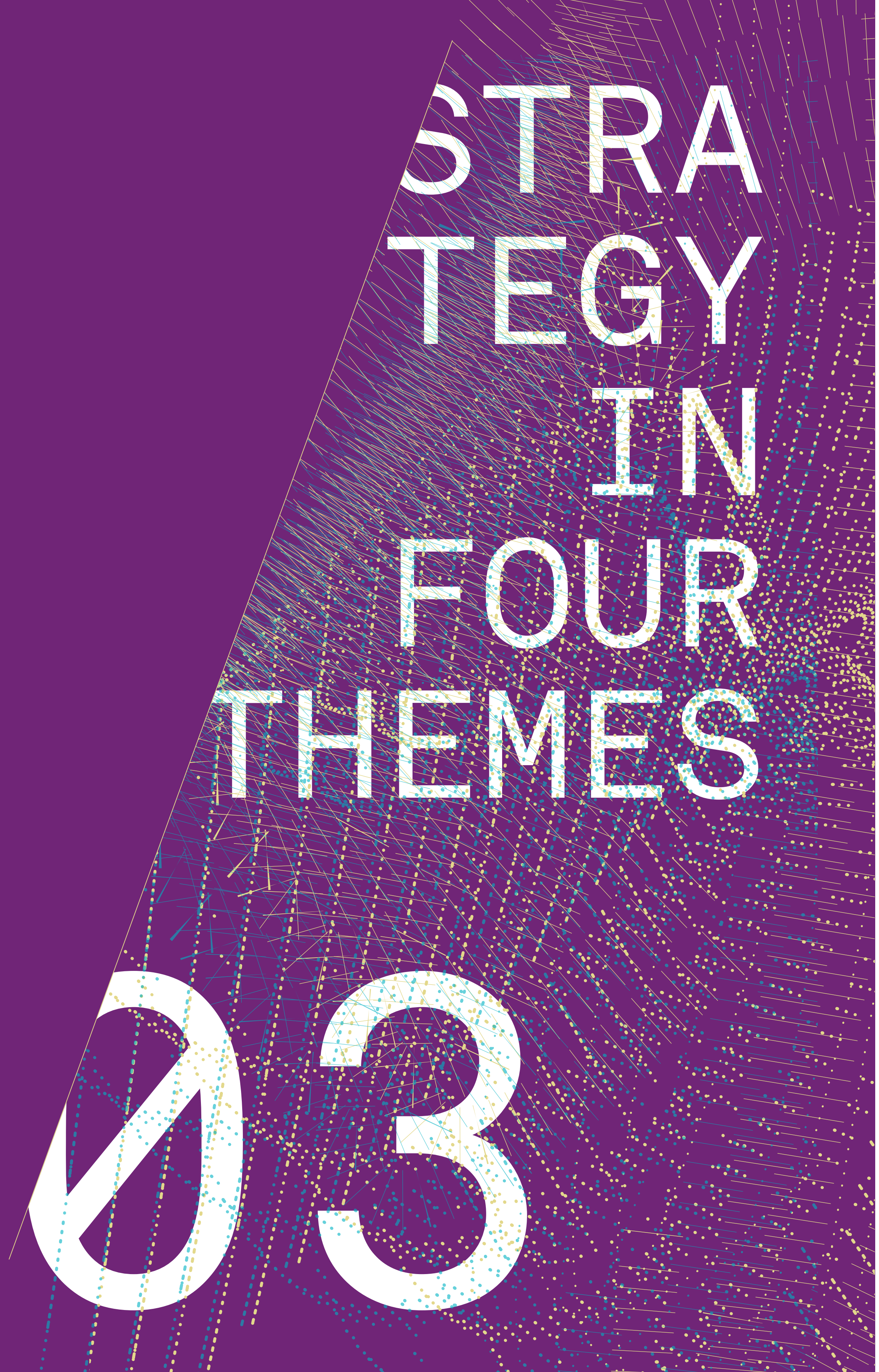
First of all, we recognise that there is in general more attention for scientific research in the Netherlands, as part of the “public good” and via the role of government in a world that calls for wisdom. The Dutch government has recently invested half a billion euro in (scientific) research and education for the next 10 years. This improves Nikhef’s chances to realise its strategy. The government has also set aside a large fund (the National Growth Fund, 20 billion euro), aimed in broad terms at the future welfare and earning capacity of the Netherlands. In its first two rounds, this fund has already shown to significantly contribute to research, development and innovation. The award for the Einstein Telescope is the most prominent example in our case.

Secondly, we observe a growing attention for “compliance and control”. In the public eye, the tolerance for human errors or random misfortune has decreased, which indirectly affects science. This puts more pressure than ever on the management and staff of the institute.

Finally, we remark that demographic developments –a population growing older on average– and technical developments such as artificial intelligence (AI) are changing society. Nikhef should remain attractive and a safe harbour for a wide variety of talents.

Internal and external developments present both challenges and opportunities (see also Chapter 5: *SWOT analysis*). It is therefore essential to continually adapt. A strategy should not be carved in stone. While conditions will vary and considerable funds are needed, this strategy document presents a clear sense of direction.

Constructing ETpathfinder at Maastricht University.



STRATEGY IN FOUR THEMES

03

The strategy's title "connecting the large and the small" applies to different contexts. Research at Nikhef connects the physics of particles to the physics that drives our universe. It literally spans collisions of subatomic particles inside human-made accelerators to collisions of black holes in the universe. The engineering connects precision mechanics and microelectronics developed in house to large research infrastructures around the globe. The physics data processing connects exabytes of data to practicable files. The theory connects an immense number of observations to a single overarching model. Finally, the partnership connects people individually and through collaborations involving thousands of persons.

As experiments become more challenging, data analyses more complex and funding more competitive, the strategy for the coming years builds more strongly on Nikhef's partnership, finding and utilising overlap between the various experiments and programmes in the Nikhef portfolio. To foster this integrated view, the strategy for the coming years has been divided in the following four main themes:

Expanding knowledge

→ Nikhef's main research effort is aimed at further expanding our understanding of the universe in terms of elementary particles and forces, through the interpretation of data, and confronting results with theory and vice versa.

Providing technologies

→ much of Nikhef's effort is put into upgrading and exploiting the current experiments and building new experiments. The technology departments at Nikhef are essential to make this happen.

Preparing the future

→ Nikhef is constantly innovating towards new technologies and designs of new facilities and projects to explore new scientific challenges and opportunities in the years to come.

Fostering healthy partnerships

→ Nikhef strives to be a vibrant, diverse and inclusive community in the (inter)national field of (astro)particle physics by ensuring a safe work environment and investing in people's talents and expertise.

These themes are detailed in the next sections. An elaboration of the strategy for each of the eleven research programmes can be found in Appendix A.

3.1 THEME 1: EXPANDING KNOWLEDGE

Following our science drivers, a considerable part of Nikhef's effort is aimed at discovering new particles or symmetries and at measuring more accurately the properties of known particles and their interactions. To spread the risk (as nature is unpredictable), Nikhef is involved in different kinds of experiments. In each, we contribute to the processing and interpretation of science data. Where possible, we confront the results with theory. In **experimental particle physics**, the search for physics beyond the Standard Model continues in all programmes, with a focus on Higgs physics, quark flavour physics, collective behaviour of quarks and gluons, neutrino properties and dark matter searches. In **experimental astroparticle physics**, the exploration of the universe goes further by measuring protons, nuclei, neutrinos and gravitational waves from the cosmos with improved statistics and resolutions. The objective will shift from first observations to studies of particles and fields under extreme conditions. In **theory**, the focus on phenomenology remains, to improve the description and interpretation of data from experiments. In **physics data processing**, artificial intelligence (AI) techniques are embraced and quantum computing is explored in order to more efficiently analyse the ever-expanding data sets that will be produced by the high-luminosity LHC and astroparticle instruments.

ATLAS, LHCb and ALICE remain core activities at Nikhef. We are now at the verge of harvesting their full potential after the upgrades in previous years to which Nikhef has significantly contributed (in 2023 the physics potential of LHCb was degraded due to an incident with the vacuum system, see also below). The science harvest will cover the full period of this strategy and likely continue up to 2040 and maybe beyond. ATLAS will focus on physics of the Higgs boson, precision tests of the top-quark and diboson processes and searches for new physics. LHCb will continue searches for (very) rare decays and new physics through various quantum loops. ALICE will study the physics of the quark-gluon plasma using the recently upgraded detector, via measurements of the diffusion of heavy quarks in the plasma as well as the interactions of high-energy quarks and gluons with the plasma.

Data taking with the KM3NeT neutrino telescopes has started but the science output will only reach its full potential upon finalisation of the construction, somewhere before 2030. The aim of KM3NeT is twofold: first, to measure oscillations of neutrinos produced in the Earth's atmosphere and to determine the mass-ordering of the three neutrino states (ORCA) and second, to observe sources of neutrinos in the sky (ARCA). With the finalisation of the upgrade of the Pierre Auger Observatory (AugerPrime) in 2024 and ARCA in the coming years, our chances to find the origin of cosmic rays will improve.

Virgo and LIGO will increase their sensitivity for gravitational waves in observation runs O4 in 2023 and O5 in 2027. This will significantly increase the statistics of observed mergers of ultra-massive (black) bodies in the universe which allows to test the theory of general relativity to the extreme. Unfortunately, Virgo will not join the O4 run from the start, as it is delayed due to commissioning issues. A detailed plan to increase the Virgo sensitivity after O4, toward O5 in 2027, is being prepared. As a member of EGO, Nikhef is strongly involved in the future plans for Virgo and in the interpretation of its data.

XENONnT will reach its optimal sensitivity for direct searches for dark matter in the coming years. Uncharted areas of the available phase space will be covered which could lead to a discovery. With new facilities being prepared, a synergistic measurement of neutrinoless double beta decay is at hand. This may eventually (dis)prove the Majorana nature of the neutrino, i.e. answer the question whether the neutrino is its own antiparticle or not.

The eEDM experiment recently entered Nikhef's portfolio. New physics —otherwise only accessible at very high energies— can be explored in house by utilising indirect quantum effects of an electron inside a trapped molecule. First science data will be recorded in the coming strategy period. The ambition is to determine the electric dipole moment of the electron with unprecedented precision. In the same spirit, physics opportunities with low-energy antihydrogen are explored at CERN.

To bridge experimental physics and theory, the Nikhef theory department maintains a focus on phenomenology. Of course, the reputation in high-precision calculations will be consolidated. The aim is to understand and interpret anomalies in the available data as well as to develop a framework for precision tests of the standard model. Studies in neutrino physics, astroparticle physics and cosmology are also pursued.

Interconnections between the scientific programmes are also being explored. A good example is GRASP, the institute of gravitational waves and subatomic physics at Utrecht University. The idea is that gravitational waves of coalescing neutron stars and the quark-gluon plasma in heavy ion collisions determine the same equation of state of matter, however in two extreme parts of the phase space.

We see opportunities in the applications of artificial intelligence (AI) and quantum computing because these techniques potentially yield faster and better science results (but we are aware of the caveats). Finally, Nikhef will also promote R&D in software (e.g. algorithms) and computing (e.g. optimising hardware with software) as a route to a future with “green computing”.

3.2 THEME 2: PROVIDING TECHNOLOGIES

Nikhef is involved in a selective number of (astro)particle physics experiments around the world. Nikhef plays a significant role in the design, construction and operation of these infrastructures, and as they progress to more advanced stages, Nikhef also contributes to upgrades and maintenance. The technical departments at Nikhef enable these commitments, which are usually driven by the science case, the opportunity to acquire additional knowhow or simply by our reputation. In the mechanical department, technicians and engineers work together with scientists to design and develop complete detectors or parts thereof. In the electronics department, designs of digital and analogue readout systems are made, including e.g. ASICs and FPGA programming. The computing department houses, together with SURF, a Tier-1 centre as well as a local Tier-2 centre, which are used for the processing and analyses of science data. The technical departments also maintain a network with other institutes and (high-tech) companies.

One can roughly divide the experiments in which Nikhef participates in operational experiments, experiments under construction, and future experiments that are still in the design phase. The latter category is the subject of theme 3.

To collect sufficient statistics for discoveries, experiments typically run for many years. As a consequence, they require maintenance and benefit from upgrades. For example, significant upgrades of ATLAS, LHCb and ALICE are made during longer LHC shutdowns. Recently, the Virgo detector and the Pierre Auger Observatory have been upgraded with contributions of Nikhef. The KM3NeT neutrino telescope is operational and under construction at the same time. Data are acquired while it is steadily growing on the bottom of the Mediterranean Sea. The list of facilities that are under construction in the Netherlands includes the eEDM experiment (Groningen) and ETpathfinder (Maastricht).

During the previous shutdown of the LHC, Nikhef made important contributions to the upgrades of LHCb, ALICE and ATLAS. For LHCb, the scintillating fibre (SciFi) tracker and the RFbox and modules of the vertex locator (VELO) were produced. In addition, Nikhef led the design of a new trigger which is based on software that runs on GPUs. For ALICE, Nikhef produced a part of the new inner tracker and a number of ITS2 modules. For ATLAS, Nikhef deployed the FELIX readout system and took part in the development of a new muon system (New Small Wheels). Today, Nikhef is responsible for constructing one of the two new inner-tracker endcaps. Following a tight schedule, the tracker will be finished in 2027 for installation. In January 2023, an incident with the vacuum system at LHCb deformed the RF box of LHCb. Nikhef is leading the replacement of this part of the detector, and will also produce new spare RF boxes.

Earlier, Nikhef made the design of the KM3NeT neutrino telescope. Now, a production line for optical modules has been set up at Nikhef. It is foreseen to continue the production of optical modules after the Dutch roadmap funding is exhausted, benefiting from Italian and French funds. Nikhef also contributed to the Tier-0 and Tier-1 software and computing.

Nikhef has been involved in the upgrade of the Pierre Auger Observatory (AugerPrime). This will yield a better separation of electrons and muons in the air showers, thereby improving the capabilities to separate protons from nuclei at the highest energies. After construction of a subset of the plastic scintillator detectors and the design and construction of the radio antennas, in the coming years Nikhef will participate in its maintenance.

For the Einstein Telescope (ET) and possibly the Laser Interferometer Space Antenna (LISA), Nikhef and companies from the Netherlands, Belgium and Germany are setting up a joint R&D facility: ETpathfinder. This facility was designed by Nikhef and is currently under construction. It will include a complete low-noise interferometer that can be used for R&D. The list of key aspects includes silicon mirrors, cryogenics (with cryogenic liquids and sorption coolers and water/ice management), ‘new’ wavelengths and new coatings. The R&D will start with two Fabric-Pérot Michelson interferometers, one initially operating at 120K and one at 15K. The R&D will also cover gravitational waves instrumentation, most notably: mirror coatings, suspension systems and low-noise quadrant photodiodes.

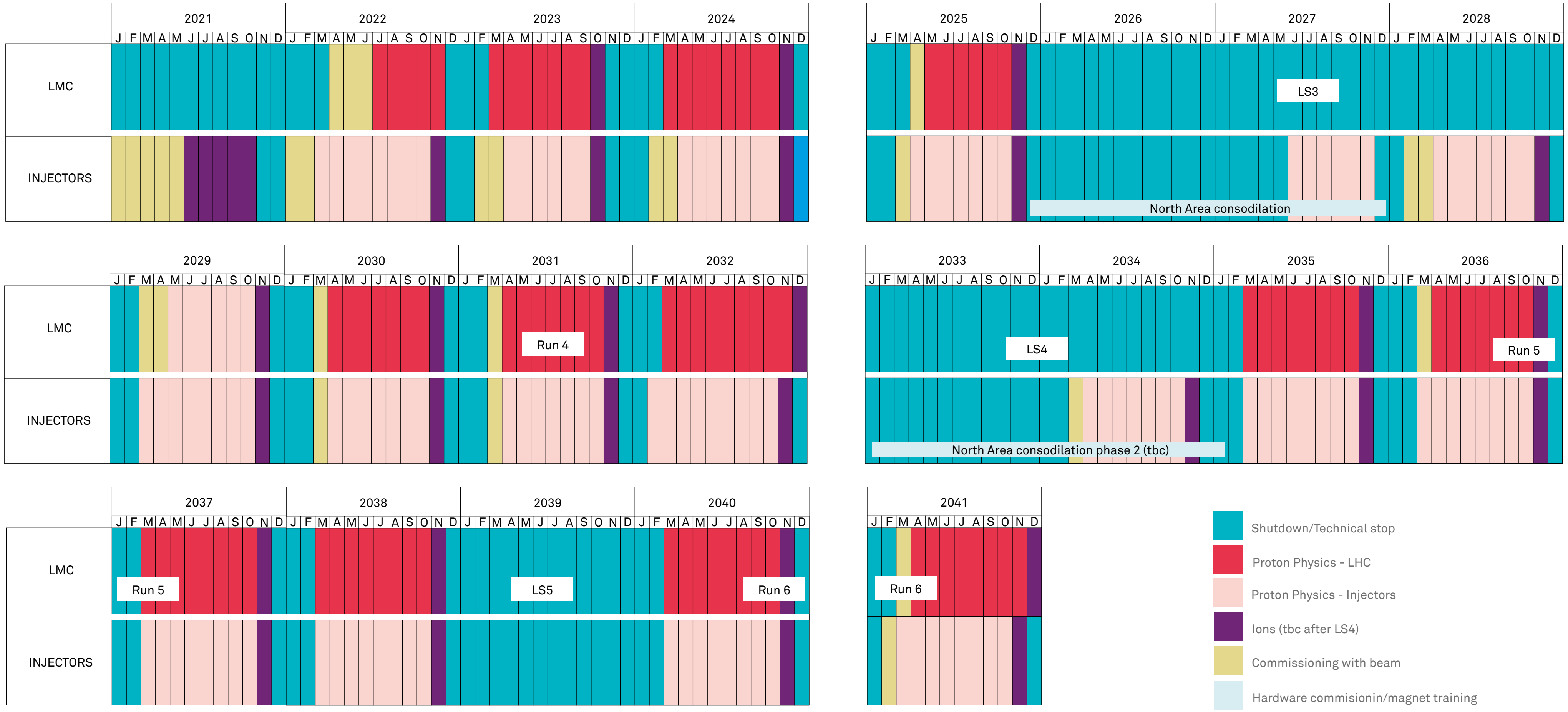
In the meantime, Nikhef will remain active in the upgrades of Virgo to increase its sensitivity. Notably the ambition to reach the projected and competitive sensitivity of the O5 run in 2027 will probably need a large upgrade of the cavities. Nikhef will participate on a basis of best effort as the financial consequences of this upgrade are not covered yet.

3.3 THEME 3: PREPARING THE FUTURE

Progress in (astro)particle physics takes time. The final design of a detector usually is the result of a careful optimisation of the performance within certain boundary conditions (e.g. cost, space, power). Sometimes, this requires thinking out of the box or bold prototyping. The construction of research infrastructures in unusual environments (e.g. in the deep sea) and large detectors (e.g. at LHC) involves up to thousands of persons from all over the world during many years. Finally, to obtain a science result, some experiments run for decades (sometimes day and night) and produce incredible amounts of data that need to be processed.

FIGURE 2 **LHC schedule between 2021 and 2041.**

Data taking periods are indicated in green. Each year during the winter period the LHC undergoes maintenance. Long shutdowns (LS) are also used to upgrade the detectors.



At the same time, one needs to think about the next generation of experiments, instrumentation and techniques and to explore new directions in the field. For the future of CERN, Nikhef is participating in international discussions on a new accelerator with suitable detectors. For astroparticle physics, there are ideas on follow-ups of current experiments (e.g. DUNE, XLZD or GRAND) as well as complete new ideas (e.g. LISA).

Nikhef is continuously investing in the development of new technologies that could lead to breakthroughs in the field. The detector R&D programme is Nikhef's main platform for these developments. A prime example is the development of high-resolution and ultrafast 4D particle detectors.

After 2030, high-luminosity operations will start at the LHC, producing much more collisions per unit time and thereby much more data. This necessitates advanced timing techniques for particle tracking in the detectors and more efficient computing. Nikhef started a joint programme with the detector R&D group, the physics data processing (PDP) group and the LHC groups. The goal is to deliver new instrumentation in LHCb, ALICE and ATLAS by approximately 2033. This programme also has a potential to deliver solutions for experiments at a future accelerator at CERN.

During this strategy period, Nikhef will formulate its position for a future accelerator at CERN. This will not be motivated by science only, but from the Dutch perspective, overall costs and sustainability will be considered as well. Possible scenarios include a Future Circular Collider (FCC) and a muon accelerator. The latter constitutes a new paradigm in acceleration of particles as the muon is a short-lived particle. The timeline for the realisation of a future accelerator extends beyond this strategy but Nikhef will participate in the ongoing international discussions on this topic and define its position in due time.

While current experiments in astroparticle physics continue to produce science data, new avenues for future experiments are explored. The avenue in neutrino physics goes from KM3NeT to DUNE, the Deep Underground Neutrino Experiment in the United States. DUNE is one of the key experiments in neutrino physics that will address CP violation in the neutrino sector. During the coming years, Nikhef intends to participate more actively in the preparations of this experiment.

EINSTEIN TELESCOPE

In cooperation with the ministries of OCW and EZK, the Limburg Province and LIOF, and with the support from the Dutch National Growth Fund, Nikhef is investigating the feasibility of a bid for the Einstein Telescope in the Euregion Meuse-Rhine. The key topics for this bid include the underground site, accessibility and spatial plan, environmental laws and local community, (civil) engineering, total cost book, commitments of partner countries, and valorisation and impact (at regional and national level). On all these aspects, a green light is needed for the bid to be submitted.

While XENONnT is reaching its maximum sensitivity, there are already ideas how to continue the search for dark matter thereafter. These culminated into DARWIN/XLZD, the "next-generation liquid xenon observatory for dark matter and neutrino physics". Nikhef is a partner in DARWIN/XLZD. Our goal is to contribute to the design, construction and operation of this new observatory and participate in the analysis of the science data.

The Giant Radio Array for Neutrino Detection (GRAND) project is a new initiative to detect ultra-high energy neutrinos using an array of some 200,000 radio antennas covering more than 200,000 square kilometres. During this strategy period, Nikhef will decide on the possible participation in the GRAND project and if so, define its contributions.

The Einstein Telescope (ET) is set to become the future gravitational wave observatory. One of the considered locations is in the Euregio Meuse-Rhine (EMR), which straddles the border between the Netherlands, Belgium and Germany. Nikhef is one of the launching partners of the ET and leads the preparation of a possible bid to host the ET in this region. If all necessary criteria have been fulfilled, including geology and financial commitments, the bid book will be submitted by 2026. After a decision about the location is made The Netherlands will become one of the members of a –to be formed– council for the ET, independent of the location. Nikhef will contribute in the usual way to the ET, also independent of its final location, and will still need to apply for funding for the scientific programme. In case the ET will be built in the EMR region, the ET will get its own organisation, independent of Nikhef.

SETTING PRIORITIES

In the future, we will also focus on a selection of key experiments in the field where we can have impact on the science as well as on the instrumentation. This inevitably implies that we do not participate in some other interesting (future) experiments. Nevertheless, some of us are involved in small endeavours that are closely related to our core portfolio and in a position to raise funds. These include PTOLEMY, FASER and KamLAND. Doing so increases the probability of finding new roads to science discoveries. We allow Nikhef members to dedicate a relatively small fraction of their time to these activities. However, the allocation of resources from the mission budget is reserved for the experiments in our strategy. Occasionally, we participate in international collaborations, such as the electron ion collider, without a formal Nikhef commitment.

In contrast to experimental particle physics, the Netherlands has more than one institute participating in astroparticle physics. Therefore, The Dutch Committee for Astroparticle Physics (CAN), with representatives from Nikhef and astronomy institutes, specifically advises on our astroparticle agenda, taking into account the APPEC European Astroparticle Physics Strategy 2017-2026. The priorities of Nikhef are in line with these recommendations.

Within this context, Nikhef will not embark on experimental activities in cosmic microwave background (CMB) and astroparticle physics with (hard) photons like CTA, as these activities are firmly positioned in the astronomy domain.

3.4 THEME 4: FOSTERING HEALTHY PARTNERSHIPS

Nikhef's partnership stands for the whole of the Dutch community in (astro)particle physics. As the partnership is growing, with relatively more colleagues affiliated with the partner universities, connections become more important. The renovation of the Nikhef building in Amsterdam (which should finish by the end of 2023) fits in this picture, as it will bring places for ad hoc as well as scheduled meetings/discussions, and offices where one can work in private. The future "Veltman centre" will be a shared place for brainstorming and topical meetings. Aside from this, equality, diversity and inclusion, open science, and sustainability will get more attention during the new strategy period. The goal is to provide a vibrant, diverse and healthy environment for all personnel. Finally, there will be more focus on onboarding of temporary and permanent staff, career perspectives for PhD candidates and postdocs, and scientific training and personal development for all who indicate an interest in this.

PARTNERSHIP STRATEGY

The Nikhef partnership benefits both Nikhef and its partners. With Dutch successes in the field largely thanks to the partnership, it should be cherished and continually reviewed and finetuned.

Beyond the partnership, Nikhef also maintains good relations with other universities, such as the technical universities, most notably in Twente and Delft, where various Nikhef scientists teach (astro-)particle physics at the bachelor and master level. With Leiden University, Nikhef (NWO-I) has joint appointments. While extending the partnership is not a goal in itself, these universities are welcome to join the research agenda of Nikhef. The required commitment to join the Nikhef partnership would be most clearly demonstrated by establishing a full professorship in experimental (astro) particle physics.

HUMAN RESOURCES

HR activities at Nikhef are focused on creating and facilitating connections between people, in the broad sense of the word. As this requires an open, inclusive and safe working environment, Nikhef substantially invests in leadership development, career support and promoting inclusive behaviour and attitudes. Also, many opportunities for meeting each other are created in order to strengthen interconnections. Examples include the annual "Jamboree", group outings, Friday afternoon get-togethers and activities of the staff association. The most recent "Jamboree" (15-16 May 2023) featured parallel sessions on sustainability and fossil fuels, and a plenary contribution on equality, diversity and inclusion.

Nikhef puts a lot of effort in giving new colleagues a warm welcome. During the first months of employment of PhD candidates a PhD introduction day is organised. New hires in all departments are actively supported with getting acquainted at the institute. New colleagues from abroad receive intensive guidance from HR at the start of employment. We offer support with practical arrangements like health insurance, taxes and finding housing. If required, Nikhef also offers support for partners of new staff members with finding work in The Netherlands. Each new colleague is also invited to a "director's lunch". In the coming years, these activities will be continued, and expanded where appropriate.

Our staff not only differ in their backgrounds, they are also employed by 7 different employers. The Nikhef HR department makes an effort to form a bridge between the employers that constitute the partnership, while respecting the conditions set by the individual universities and NWO-I. Within this context, we have a policy of holding regular meetings with every Nikhef employee, regardless of their formal employer. In the coming strategy period, the recommendations of the NWO-I report entitled "Recognising and Rewarding Talent in Today's Academia" will be implemented in these meetings. Where needed, these recommendations will be tailored to the specifics of Nikhef's partnership, where teamwork is key (rarely a paper is written by a single person) and time-consuming leadership roles limit opportunities to publish papers.

Nikhef will continue to offer coaching on healthy work-life balance as well as workshops (organised by NWO-I) on topics like 'dealing with stress', 'healthy sleeping' and 'Mindfulness'. The PhD council organises a buddy system for PhDs, acts as an point of information for PhDs, and also organises serious and social activities. It is foreseen to extend or supplement the PhD council with a similar council for postdocs.

Finally, the best research is made in a climate where opposing ideas are welcome, questions explained and mistakes gauged. Everyone should feel comfortable and safe, regardless of specific individual characteristics such as, for example, skin colour, cultural background, gender, gender expression and gender identity. It has been recognised that these aspects deserve more attention. Following the successful implementation of the Gender Equality Plan, work is now underway on the Nikhef Diversity & Inclusion plan. The development is supported by a recently installed 'Diversity & inclusion Taskforce' and is planned for completion by the end of 2023. The D&I plan will be executed in the coming strategy period.

PHD POLICY AND TRAINING

Each of the 120 PhD candidates within the partnership is embedded in one of two graduate schools, namely OSAF for experimentally oriented research and DRSTP for theoretical physics. These graduate schools provide training, education, supervision and mentorship. For OSAF, the activities are coordinated by the Nikhef education committee (*onderwijscommissie*, OWC) where all university partners are represented. The university partners usually also maintain research schools in which PhD candidates participate. The OWC ensures that the various research schools are well aligned.

Several times per year "topical lectures" on for example Higgs, statistics, machine learning, instrumentation or cosmic ray physics are organised at Nikhef, aimed at all PhDs, including those not directly involved. These lectures typically run for a couple of days and include exercises and self-study. PhD candidates are also encouraged to visit the biweekly colloquium (often involving outside experts talking about recent developments or new ideas) and the "theory meets experiments" get-togethers (where experimentalists and theoreticians discuss in a very informal setting). PhD candidates under OSAF should attend (at least) two BND graduate schools, which are two-week schools on experimental (astro)particle physics for PhD candidates working in Belgium, Dutch and German institutes. In addition, Nikhef offers various training courses on e.g. computing, data management, science data integrity and communication skills. Of course, PhD candidates also benefit from training activities organised by NWO or our university partners, for instance the "Taking charge of your PhD" course and the "Introduction to Dutch language and culture course".

Key to efficient and transparent PhD supervision is the C3 mentorship scheme, where a staff colleague from another research group chairs regular meetings with the PhD candidate to monitor the timelines and discuss possible issues. These meetings may be with or without the supervisor(s). In case of (mental) issues or conflicts, the C3 chair points the PhD candidate to a confidential councillor or the company doctor. To improve the supervision, Nikhef also provides designated training to the supervising staff. Note that all regulations and guidelines from OSAF are available via its website, and OSAF is open for feedback from PhD candidates and (supervising) staff.

Finally, the Nikhef partnership exposes PhD candidates to a great variety of academic environments, from small working groups to large international collaborations. They can present their work at collaboration meetings, the annual meetings of NNV in Lunteren, Physics@Veldhoven and international conferences. This contributes to a broad horizon and open mind, while providing valuable experiences for a career in science or anywhere else. Nikhef helps PhD candidates to explore employment opportunities in industrial and societal sectors.

AGILE WORKING

A handful of pilot projects in the Nikhef technical departments have adopted Agile working. For example, the ATLAS inner tracker project uses Scrum. These transitions involve both organisational and cultural aspects. The current experience is that these teams are more efficient and their members get more satisfaction: a win-win. As expected, there is less risk of micromanagement because the technical staff have more autonomy and the project leaders convey more trust. Our ambition for the coming years is to apply Agile working to all technical projects at Nikhef. Last year, a few staff members were trained in Agile working and one of them also decided to become an Agile coach. The latter provides in-house coaching for (new) project leaders. During the coming strategy period we will take stock of experiences and explore if Agile working could benefit other parts of the organisation, too.

ACADEMIC CULTURE

The Nikhef partnership brings together a colourful collection of students, scientists, engineers and technicians, performing a broad range of activities such as research, engineering, data analysis, training and teaching. Far from a rigid hierarchical organisation, our *modus operandi* is open and flat. As a result, people feel free to exchange ideas, ask questions and discuss problems. The participation in international collaborations broadens our horizon.

Despite the partnership's size and range, people know who does what. There is a central spot at the Nikhef institute where people meet daily, and plenty of occasions where people from different programmes interact (e.g. regular "theory meets experiment" get-togethers and "made@Nikhef" events). Every two months, the director reflects during a "spiegelmoment" on the activities within the partnership, the developments in the field, and practicalities (e.g. refurbishment of the building). This is also the moment when new colleagues are introduced.

Within the partnership, we keep a close eye on the balance between research activities, lecturing at universities and other duties (e.g. leadership roles, committee roles). When possible, we try to release the pressure to submit funding proposals by focussing on calls that fit our ambitions.

Communication of science and technology to peers usually happens in the form of peer-reviewed publications but nowadays, arXiv is widely used as an alternative. An unwanted side effect of today's publishing culture has been that publications/citations have become a measure for the quality of a researcher. We adhere to the primary purpose of publications and follow authorship conventions in the field: everyone who contributed to the final result is listed, including those who developed the software, calibrated the detector and analysed the data. A requirement is that they are members of the collaboration although exceptional contributions from outside can be recognised with an authorship of a specific paper. For technical papers, the list of authors is often defined on a case-by-case basis. For conferences, a person is usually selected by a designated committee that has been set up by the collaboration. The list of authors may then be reduced (down to a single person) but one generally speaks on behalf of the entire collaboration. Special recognition is granted to those who are invited à titre personnel, convene a session or give a summary talk.

Knowing the time and effort it takes to make a discovery in (astro) particle physics, academic freedom is paramount. At the same time, a science result is only valid by the statistical significance of the data and the quantification of the systematic uncertainties of the measurement (or similarly, the accuracy of the calculation). Within the Nikhef partnership and (astro)particle physics in general, we hold on to a threshold of 5-sigma significance for a discovery, taking into account the systematic uncertainties.

In view of the large investments in designing, building and operating (astro)particle physics experiments and the required efforts to process, analyse and interpret the data, an embargo period is foreseen before making the data open. The types of data (e.g. raw, processed, calibration or simulated data) as well as the embargo period (e.g. two years) are subject/result of discussions within the collaborations.

Finally, the success of the Nikhef partnership did not come out of the blue but is the result of operating for almost 50 years in the field and learning along the way. For the coming strategy period, we will continue to learn, adapt and improve.

NIKHEF SUSTAINABILITY ROADMAP

Nikhef's aims to be climate neutral in 2030. This ambition is detailed in our Nikhef Sustainability Roadmap, which was released at the end of 2021. A midterm evaluation of the Nikhef Sustainability Roadmap actions is planned for 2025. Nikhef commissions a CO2 footprint analysis every year. For 2019, 2020 and 2021, Nikhef's total footprint was 1.082, 407 and 306 tons of CO2, respectively. This decrease can be attributed to the COVID pandemic during which business and commute travel was reduced to an absolute minimum. In 2022 the footprint increased again to 521 tons, mainly due to air travel being resumed, but still only a third of the 2019 figure.

From the 2019 data, we have learned that long-distance (in particular air) travel contributes the most, accounting for two thirds of the CO2 emission. The remainder of the footprint is attributable to use of natural gas (building heating) and commuter traffic. The contribution from computing is negligible because the electricity that is purchased is sustainably produced. In the Nikhef Sustainability Roadmap, five lines of action are described, namely:

1. Travel

To reduce the footprint due to travelling, we should travel only when there is no other option; when travelling, we should use sustainable forms of transportation; and as a last resort, we should compensate. To achieve this goal, our first approach is to create awareness and motivate staff to travel sustainable. Other approaches (such as policies, prohibitions or obligatory actions) will only be considered when needed. Nikhef facilitates finding sustainable travel options by providing tips and tricks on its internal website. The results of the 2022 footprint analysis provide grounds for moderate optimism: air travel has not bounced back to pre-COVID levels, whilst (international) travel by public transport (train) has indeed increased.

2. Energy for the building

The Nikhef building in Amsterdam Science Park is being renovated. When finished, we will be off the gas grid, thanks to good insulation and reuse of residual heat from the data centre. Cooling will be provided by a sustainable cold source in the ground. Electricity that is purchased by Nikhef is produced sustainably in the Netherlands. Nikhef plans to add solar panels to suitable areas on the roofs.

The data centre is currently responsible for about 80% of the total electricity demand (about 10 GWh/year). We have taken measures to reduce this energy footprint, such as applying cold corridors and cooling with a cold source in the ground. This underground energy exchange allows the student housing across the street in the Science Park to be heated by the data centre. We estimate the equivalent energy value of this reuse to be about 1,7 GWh/year. Together with the reuse of the heat for the Nikhef building, this makes the data centre very energy efficient.

3. Waste

Together with our partners at the Amsterdam Science Park, we are working on separate waste collections to improve recycling of raw materials. Sustainability will also be part of procurement procedures. As the equipment itself also contributes to the CO2 footprint of the institute (not included in the reported footprint), all personnel are encouraged to keep equipment longer and only use it when needed.

4. Behaviour/attitude

True sustainability requires a top-down as well as a bottom-up approach. The latter is achieved by stimulating a change in attitude and behaviour of the personnel. As an example, the works council suggested only funding vegetarian lunches and dinners, which now is endorsed by the Nikhef directorate. Sustainability is regularly discussed in staff meetings and events such as the Nikhef jamboree. One of the goals is to increase the awareness of the effects of our current behaviour and actions we take as scientists on the carbon footprint of the institute.

5. Primary process – sustainable (astro)particle physics

We are learning to pay attention to all sustainability aspects of our experiments. Ultimately, this should cover design, construction, operation and dismantling of the detectors as well as energy use of (future) accelerators, computing and travel. This goes beyond this strategy document but it is part of our ambition: as members of scientific collaborations, we feel it as our duty to help put sustainability prominently on the agenda of our experiments. As an example, a preliminary study on the sustainability aspects of the Einstein Telescope in the EMR region has been made which includes options such as limiting transport movements and reuse of excavated rock. Another example is a study on the carbon neutral operation of the KM3NeT deep-sea telescopes, which turned out to be favourable in terms of overall costs.

VALORISATION

Curiosity-driven as it is, even fundamental research in subatomic physics like at Nikhef naturally has connections to society. Deep scientific questions are studied through advanced technologies that find applications or adaptations in industrial products. There are well-known examples of applications that originated in our field, such as the world wide web and the touchscreen, both originating from CERN. A lesser-known example is the development of colour X-ray tomography driven by the efforts of the CERN-based Medipix collaborations of which Nikhef is a founding member.

Societal impact of Nikhef research ranges from spin-offs to joint innovation and co-creation. For instance, the application for the National Growth Fund for research into the feasibility of the Einstein telescope was accompanied by more than 50 recommendation letters from industry, implying that the techniques being developed for the ET are of value to industry. Earlier companies in PET and fluorescence labelling technologies explicitly expressed their interest in extremely sensitive light sensors (PMTs) being developed for the KM3NeT neutrino telescope in the Mediterranean.

The importance of societal impact runs broadly through the Nikhef organisation, but two activities deserve explicit mention. First, the R&D group is mandated to collaborate with other R&D groups as well as industrial partners. Second, knowledge transfer is staffed with Industrial Liaison Officers (ILOs), e.g. for CERN and the ET. They make connections with companies and promote collaborations. In The Netherlands, we play a leading role in the BigScience.NL network of ILOs, comprising many high-tech companies who meet regularly to further their involvement in the domain of Big Science.

OPEN SCIENCE

Nikhef thrives on open collaborations, open access to research infrastructures and open data. Open science, however, involves much more than that. For example, deposition of science data that are not accompanied by the necessary digital competences may result in “dead” data. Nikhef strives to adhere to FAIR data and open science in general. It has taken the initiative in shaping open science within the partnership and participates in pan-European activities in this direction. Within the international collaborations, Nikhef promotes open science practices along four lines of action: (i) stimulating Dutch activities on integration of software, data and computing as a coherent system through the Thematic Digital Competence Centres for the natural and engineering sciences, the Netherlands eScience Center and the SURF national e-Infrastructure; (ii) investing in expertise for science data management to maximise the benefits of reusing science data and research software, in conjunction with data storage and processing infrastructures; (iii) using open access for publishing science results, aiming at gold and where feasible diamond (98% of our papers are open access, according CWTS) while supporting the SCOAP3 collaboration and using OSI-approved open source licensing and the re-use-friendly Apache2 license (minding open source license deconfliction requirements) for software developed by us; and (iv) encouraging versioned and open-workflow publications (e.g. via Jupyter notebooks and Snakemake) to present data through computing and data management training, and supporting the development of repositories that enable continuous data deposition.

By preference, Nikhef makes use of community domain-specific repositories for data as well as software. For example, data related to our collaborations are deposited in repositories maintained by the collaboration (usually the host laboratory, e.g. CERN), theoretical calculations are deposited in HEPForge, and seismic data from the Einstein Telescope site surveys are deposited in the repository of the Royal Netherlands Meteorological Institute (KNMI). As we see open science as a continuous process in our programmatic research methodology, we target a continuous deposition and re-use model rather than focus on the more static ‘replication package’ approach. We see this as especially relevant for multi-messenger (astro)physics and gravitational waves. For small-scale experiments we also establish an institutional repository, in collaboration with 4TU.ResearchData. Finally, scholarly data (e.g. lecture notes) are deposited in repositories of the university.

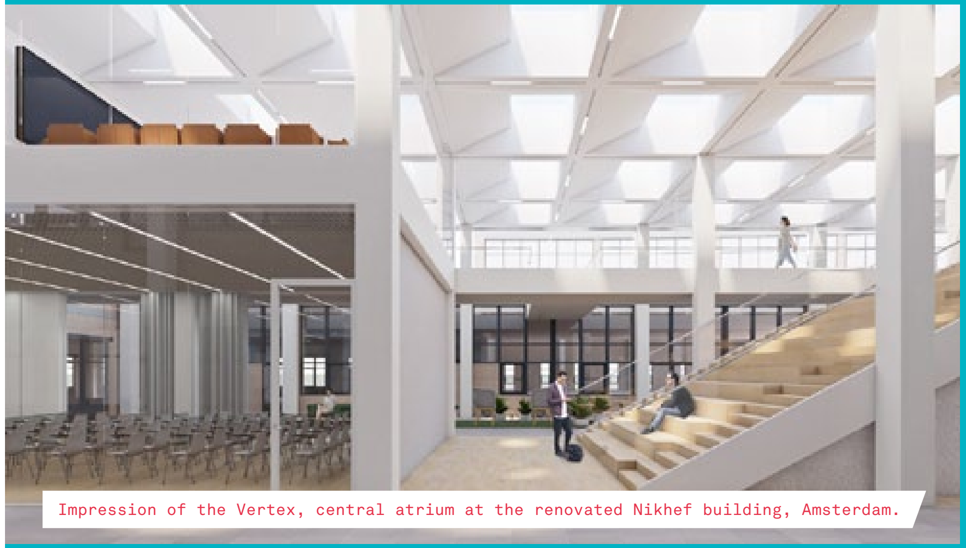
EDUCATION, COMMUNICATION AND OUTREACH

We put great effort into inspiring and preparing the next generation of scientists, through programmes for school children and teachers, to Bachelor’s, Master’s and PhD programmes. At the elementary school level, we promote science literacy and encourage young students to develop a keen interest in science, for example by giving presentations at schools, organising science fairs and offering online resources. At the high school level, we engage students by offering them opportunities to work alongside scientists in our institute, and teachers by suggesting experiments suited for school exams. Through internships, research projects and other activities, high school students are able to gain hands-on experience. At the university level, we give a number of lecture courses and supervise students pursuing a Bachelor or Master of Science degree.

To support communication lines with society, our communication and outreach office maintains good contacts with Dutch media. We are also well connected to foreign media through the EPPCN network of communication professionals in particle physics. The office publishes science projects and results and organises visits to the institute, and develops educational programmes and hands-on materials. Last but not least, it provides help and training for staff and PhD candidates who want to contribute to outreach activities. In this strategy period, more attention will be paid to gender balance in the publicity and outreach programmes.

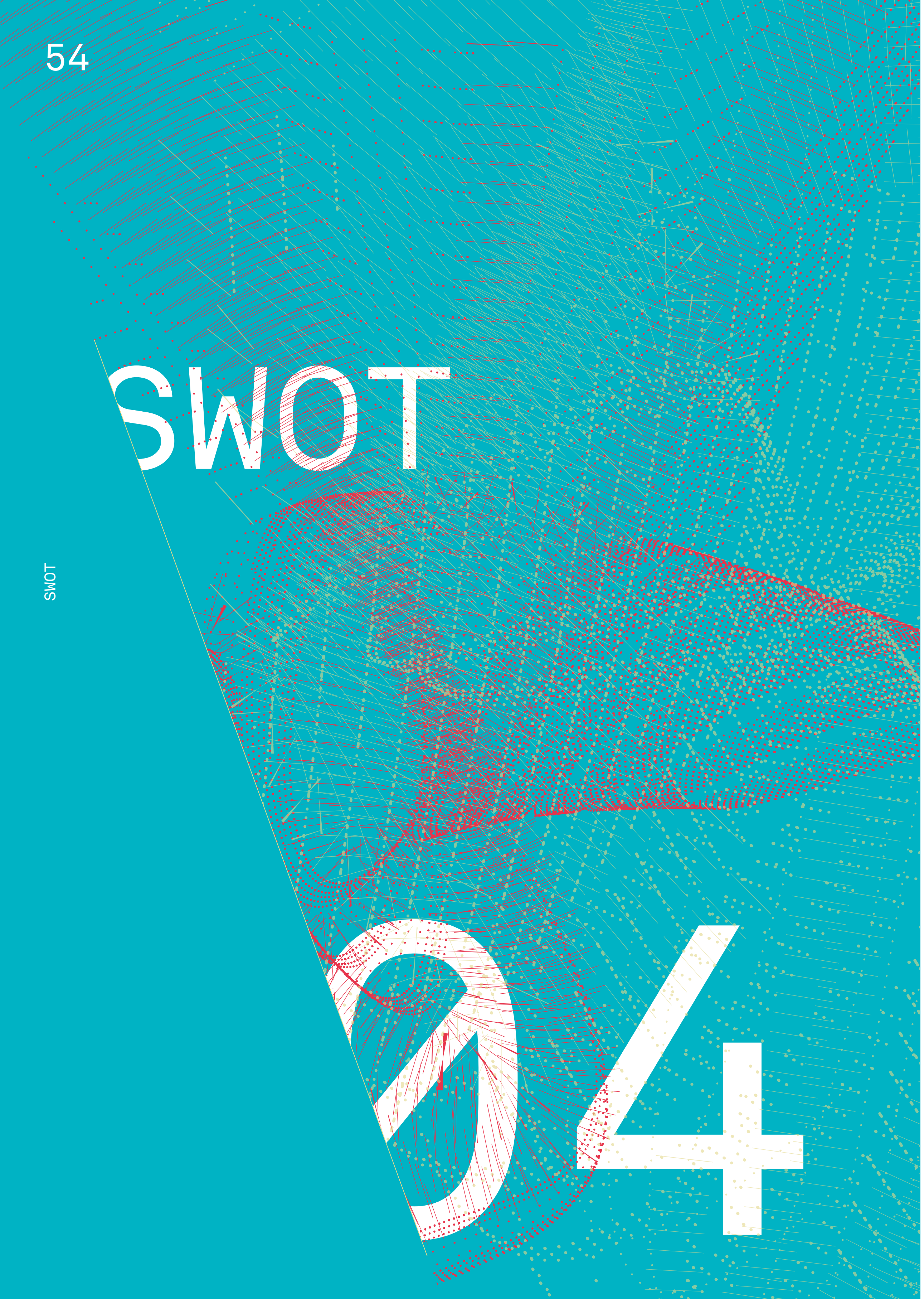
We publish on our website nikhef.nl daily news in Dutch as well as English. Twice a year we publish the magazine DIMENSIES (Dutch only) on paper and online. These communications are aimed at the general public but may also serve policy makers. One day a year, Nikhef as well as other institutes at Science Park organise an “open day”, which is well visited. Nikhef staff and PhD candidates also give many (evening) lectures for the laymen and the many times they act as host for our visitors. In communicating to this wide variety of audiences, our key message is that fundamental research, like (astro)particle physics, is done by humans and for humans.

Finally, we look forward to open the doors of the Nikhef building after the renovation. There will be a “showlab” where visitor groups can see detectors at work and follow lessons, an exhibit in the central hall showcasing (astro)particle physics research in general and highlighting Nikhef’s contributions, and public lectures in the new auditorium. During the coming strategy period, extra effort will be put into reaching less-privileged groups through visits and invited talks to targeted schools in the Amsterdam area mainly.



Impression of the Vertex, central atrium at the renovated Nikhef building, Amsterdam.

Preparing the ITK endcap for the ATLAS detector.



SWOT

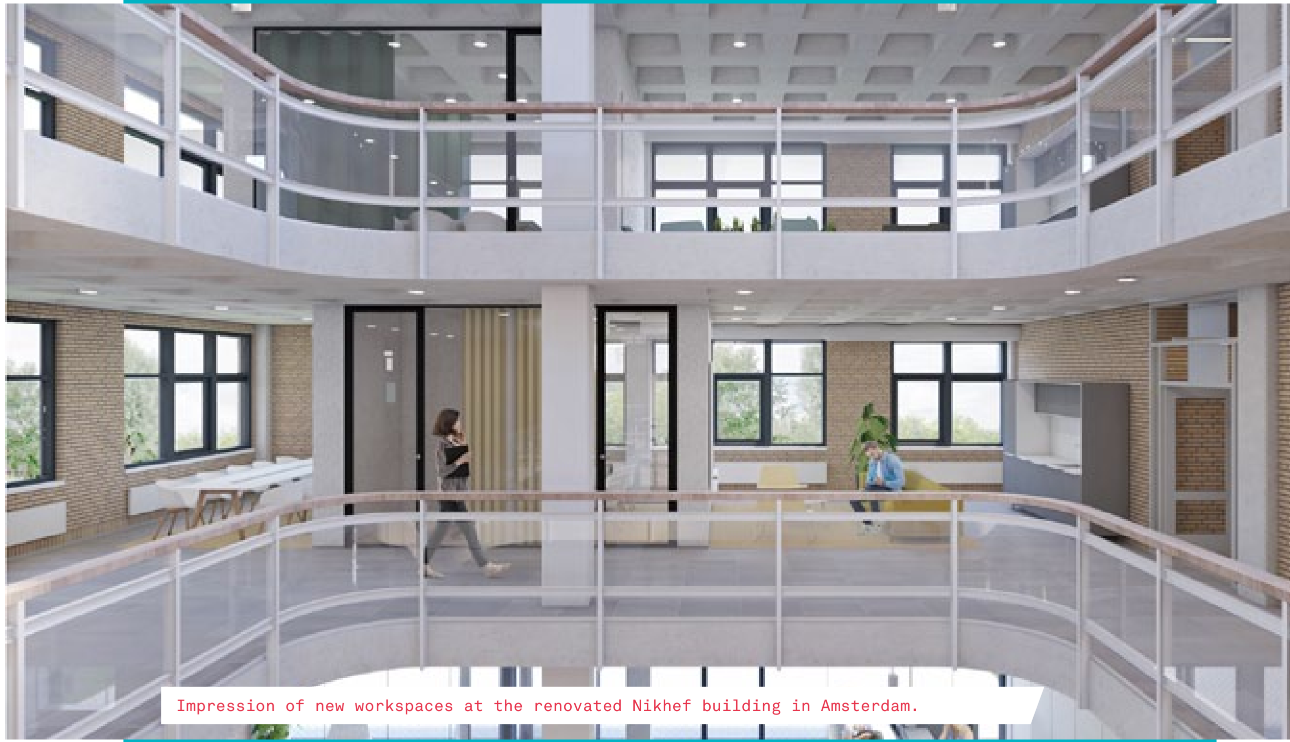
04

Strengths	**Actions**
All Dutch activities in (astro)particle physics are organised within one partnership.	Maintain a coherent community in The Netherlands.
Rich and balanced science portfolio.	Continue evaluations of ongoing projects and discussions on future prospects.
Motivated and skilled personnel with proven leadership in the field.	Offer training and courses to personnel and support persons in leading roles.
Open and safe work environment.	Invest in inclusive culture and leadership, invest in personal well-being and keep organisation flat.
Large impact in design, construction and operation of detectors as well as in processing, analysis and interpretation of science data.	Consolidate commitments and carefully select new opportunities.
Computing infrastructure fits well with experiments.	Maintain position and expertise in running and innovating infrastructure.
Genuine interest of the public in (astro) particle physics.	Maintain a strong network in press and invest in outreach via social media.
Viable eco-system consisting of instrumentation, data analysis and theory interpretation	Continue to leverage this eco-system to generate impact in all areas of our profession
Proven scientific entrepeneurship	Keep ambitious agenda for scientific activities

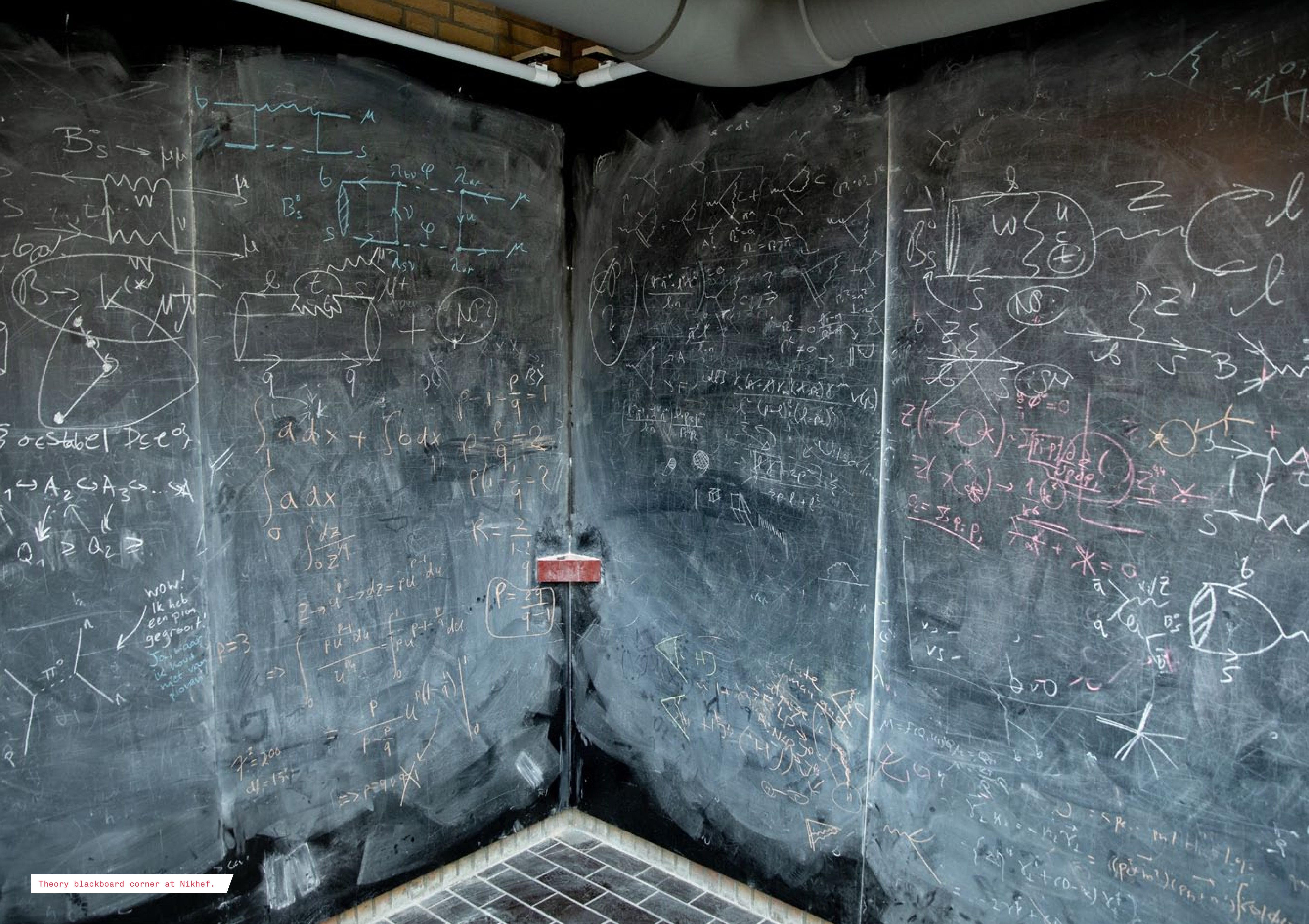
Weaknesses	**Actions**
Inclusion can be improved: Nikhef staff shows a diversity imbalance in leadership roles.	Follow up on D&I taskforce, instruct staff in leading positions and guide targeted persons (to the top).
Long lead times and durations of science projects.	Define core activities and make long-term plans in order to retain enough personnel and expertise in long-term experiments.
Lack of recognition from LHC collaborations for Dutch/Nikhef computing resources (LHC-Tier-1).	Propose compensation rules to CERN/ LHC experiments.
Open science cannot be implemented by a single institute.	Discuss common guidelines and work out detailed solutions within collaborations.
Difficult to find cohesion between all particle- and astroparticle groups	Cross group scientific and social events

Opportunities	Actions
Exploit precision physics at LHC.	Analyse data from Run 3 and prepare for LHC high-luminosity upgrade.
The Nikhef design and technology is well visible in the ambitious upgrade plans of the LHC experiments.	Stimulate close involvement of technical departments.
Neutrinos and neutrinoless double beta decay as roads to CP-violation and the Majorana nature of particles. Dark Matter searches for new particles.	Invest in corresponding (astro)particle physics experiments.
Gravitational waves offer opportunities to study space-time.	Participate in gravitational waves experiments and data analyses.
Interest in hosting Einstein Telescope in EMR region.	Work towards a bid book.
Benefit from in-house infrastructure and science.	Pursue eEDM programme and ETpathfinder.
National research institutes are now organised under one umbrella organisation (NWO-I).	Pursue joint activities and propose common projects.
The increased diversity of the Nikhef staff population offers the chance to increase diversity in leadership positions.	Stimulate and support staff members from underrepresented groups to develop leadership skills and to take up leading roles.

Threats	Actions
Individual experiments may fail to yield results.	Spread risks in science portfolio and advocate astroparticle physics within CERN.
Compensation of mission budget for inflation may not be granted.	Make the Board of NWO-I aware and negotiate solutions.
The award of the National Growth Fund grant for the ET may be misunderstood as an increase of research budget.	Make financial implications clearer to the policy and decision makers.
The bid to host the ET may be unsuccessful, which may be perceived as a failure from Nikhef.	Be transparent on all aspects of the feasibility study (investigations of geological, societal and financial impact and risks).
The scope of gravitational wave activities may exceed the scale that can be managed by Nikhef alone.	Explore alternative management structures and consult with CERN.
Individual members, especially young persons, are relatively invisible in large collaborations.	Support for (young) persons to make their contributions concrete and visible.
The recognition for instrumentation lags behind theory and analysis. In addition, the high-tech sector is in high demand with technical students, making it harder for us to attract the ‘best’ students.	Being a member of the taskforce “ECFA Detector R&D Training Panel”, which aims to (1) establish and maintain a European coordinated programme for training in instrumentation, and (2) develop a master’s degree programme in instrumentation.



Impression of new workspaces at the renovated Nikhef building in Amsterdam.



Theory blackboard corner at Nikhef.

FINANCIAL AMBITIONS 2023 → 2028

05

5.1 \ NIKHEF NWO-I: MISSION BUDGET

This section describes how Nikhef intends to fund its strategic agenda for the coming period.

Per 2023, Nikhef (NWO-I) avails over a mission budget of about 17.8 M€. This mission budget is assumed to be a 'guaranteed' funding stream, to contribute to the mission of Nikhef, the amount of which is subject to the mission evaluation, taking place every six years. The mission budget alone is a small share of the total revenue needed to run our science programme. Therefore, submitting proposals for grants is an ongoing activity of scientists at Nikhef.

The Nikhef partnership is in need of stable funding instruments fit to cover large and long term (10+ year) programmatic activities, for the scientific exploitation (through PhD and postdoc positions) of our experiments (at the LHC and at the astroparticle physics detectors). Currently, two funding instruments might suit this goal:

- The NWO Gravitation grant is a funding instrument of NWO (open every three years) for programmes of 10-year duration, targeted at nation-wide consortia of the highest scientific quality in the Netherlands. In January 2023 we submitted a 24.4 M€ proposal in this scheme on Gravitational Physics research.

- The NWO Summit grant is a new (probably one-time) funding instrument of NWO. This call is targeted at excellent, proven, existing scientific collaborations. A grant may vary from 15 to 40 M€ for a 10-year duration. Probably less than 10 consortia nation-wide will be granted. In June 2023 Nikhef submitted a ~25 M€ pre-proposal, centred around its LHC physics activities.

However, the outcome of these calls is unsure and therefore we still have to manage the risk that we cannot exploit the physics potential of experiments we have previously designed and built. To partially and temporarily overcome this risk, the Nikhef management aims to free part of its mission budget (~ 2 M€/year, equivalent per year to about 7 new positions, either four-year PhD graduates or three-year postdoc positions), to support the scientific exploitation of its experiments.

5.2 \ ADDITIONAL (PROJECT) FUNDING

Apart from the long-term NWO calls mentioned above, Nikhef will strive to obtain additional funding (from NWO, EU and all other available funding sources) for PhD candidates, postdocs and other personnel (working e.g. on engineering efforts) of 6 M€ annually. This is twice the amount of the previous strategy period. This high ambition is given by the fact that we generously achieved our previous goals, hence we currently expect this to be achievable. We will continue to help staff with preparing grant applications in all possible ways needed, such as internal review mechanisms, external text editors (science writers), and interview and presentation training.

5.3 \ INVESTMENTS

Nikhef will aim for several investment funding opportunities in the coming period:

National Roadmap of Large-Scale Research Infrastructures

The National Roadmap funds have been extremely important for Nikhef and will continue to be so in the coming strategy period. It is the prime source for our contribution to upgrades of our experiments.

For the 2024 round, Nikhef intends to submit a ~20 M€ proposal on '4D Fast timing', to enable our ambitions for the upgrades of the LHC experiments. In the same 2024 round we also plan a ~10 M€ proposal for Neutrino Physics (DUNE) and Dark Matter (XLZD).

For the 2026 round, Nikhef currently aims to submit a proposal for the instrumentation of the Einstein Telescope. The ambition is to request funding in the order of 25 M€, independent of the outcome of the site selection. However, the timing of this request might be subject to change, as this needs to be coordinated with the planning for the bidding phase. It may well be that for the further future, around 2032, Nikhef will submit a second proposal of ~25 M€ for the Einstein Telescope instrumentation including computing needs.

Also in 2026, and dependent on developments regarding the funding of the national e-infrastructure (computing, data, etc.), Nikhef may need to submit a funding proposal for another five years of WLCG Tier-1 and KM3NeT computing investments, as a follow-up of the FuSE project. As we have done with FuSE, we intend to keep teaming up with our astronomy colleagues, in particular SKA, since the size and character of the data processing challenges is comparable.

Depending on the outcome of our deliberations on participating in Ultra High Energy Cosmic Rays experiments (GRAND), Nikhef intends to submit in the 2028 call a proposal for the instrumentation of this experiment, amount yet to be determined.

NWO: Research infrastructures – national consortia

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 2024 and 2026, Nikhef will consider submitting proposals for Auger, Virgo and/or Xenon. This needs to be further worked out and timed, depending on the needs of these experiments.

5.4 \ NET INCOME FROM THE DATA CENTRE

The market perspective of the Nikhef data centre is still very good. Nikhef has always focussed its attention on being a facility for interconnection, which has led to a unique concentration of connected networks at the Nikhef site (#6 in Europe and #11 worldwide, according to peeringdb.com). Thanks to the extension we expect the turnover of the data centre to increase to about 6 M€ annually in the coming strategy period. The investment costs for the extension will be earned back with the extra turnover generated in about 7 years. Running costs have unfortunately also increased, in particular energy costs. This has forced Nikhef per 2023 to raise its housing and connection fees by 10%; further price increases cannot be excluded. Until now this has had no adverse effect on our customer base. All in all, we expect the net operating result of the data centre to increase to about 2.5 M€ annually.

The table below summarises the funding targets for the coming period.

TABLE 2 **Nikhef funding targets for 2023-2028**

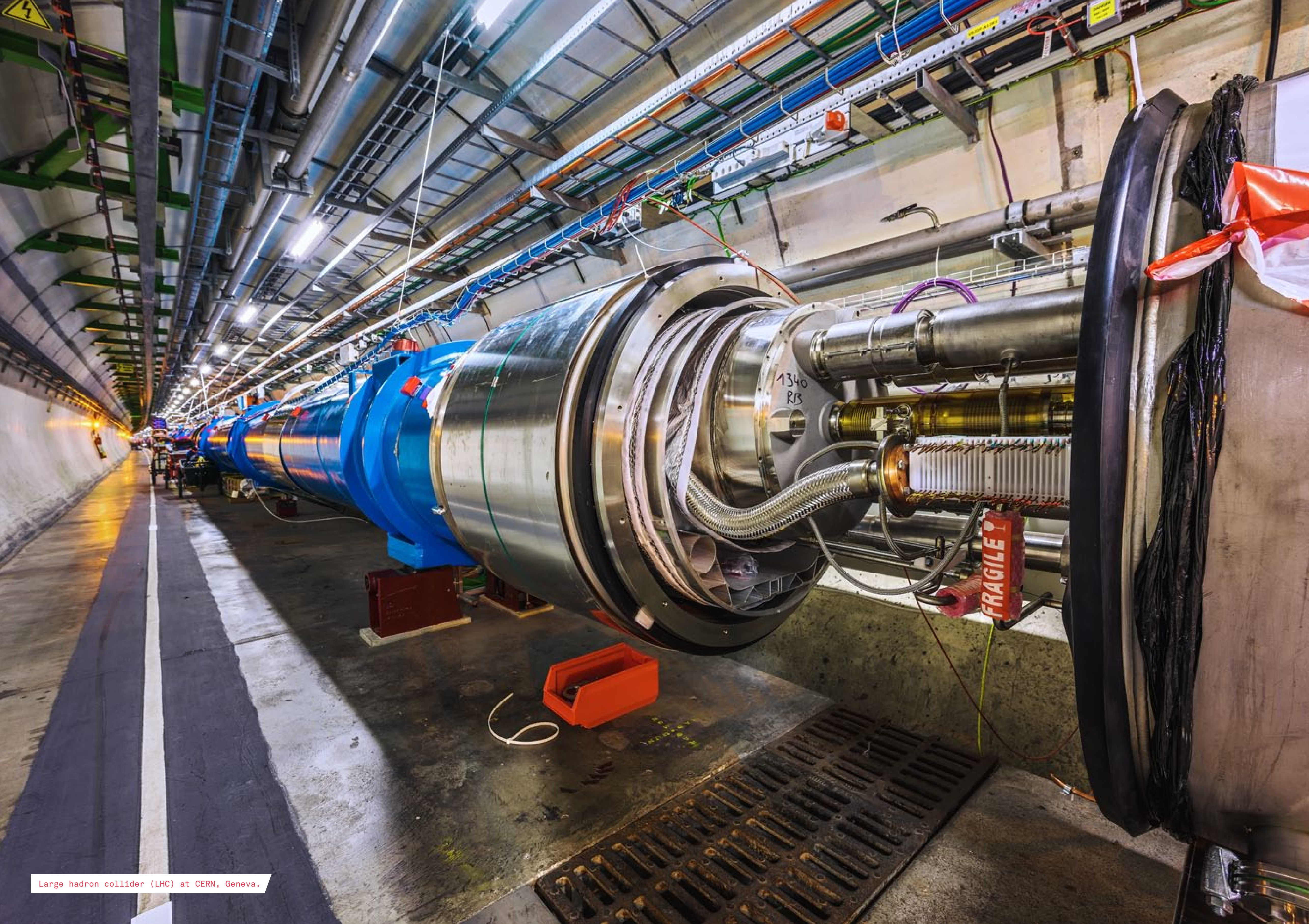
(Research) activity	Year(s)	Funding target
LHC physics, astroparticle physics	2023-2028	Obtain long-term (10-year) programme funding from NWO for postdocs and PhD candidates, amounting to ~2.5 M€ annually, using the NWO-Summit instrument
LHC physics, astroparticle physics	2023-2028	Obtain an NWO-Gravitation grant: ca. 25 M€ for 10 years to strengthen the Dutch (astro)particle physics activities with tenure track positions, temporary scientific staff and moderate investments.
All research activities	2023-2028	Obtain additional funding (from NWO, EU, etc.) for PhD candidates, postdocs and other personnel (working e.g. on engineering efforts) of 6 M€ annually.
Data centre	2023-2028	Increase net operating result to 2.5 M€ annually
LHC experiments	GWI 2024	Obtain investment of 20 M€ for upgrades ('4D Fast timing')
Neutrino physics, DM	GWI 2024	Obtain investment of 10 M€ for DUNE & XLZD
Einstein Telescope	GWI 2026	Obtain investment for instrumentation in the order of 25 M€. A further investment request for instrumentation and computing is foreseen for beyond 2030.
LHC experiments – Tier 1	GWI 2026?	Obtain investment of 6 M€ for Tier-1 to run for another 5 years. Timing yet to be determined.
UHECR	GWI 2028	Obtain investment, dependent on further strategic choice.
Auger, Virgo, Xenon	WI 2024-2028	Investment per experiment of ~3 M€; to be further timed and prioritised.

5.5 \ MISSION BUDGET INCREASE

Our long-term programmes need a long-term perspective, which is not sufficiently present in the predominantly short-term national funding competition. This poses a major risk for the partnership in terms of obtaining continuous funding for the scientific exploitation (i.e. temporary scientific personnel: postdocs and PhD graduates) of the long-term experiments on our strategic agenda. Nikhef's mission budget, residing at NWO-I, is the most important source with which this misfortune can be mitigated and for which we would like to reserve in the order of 2 M€ annually. However, as explained in the self-evaluation, the increase in our mission budget in the last strategy period has not kept up with increasing inflation (prices and salaries), rendering a spending power deficit of about 0.7 M€. An additional budget cut implemented per 2024 will increase this deficit with another 0.3 M€.

Other figures corroborate the stress on our (NWO-I) mission budget as a 'steering instrument' for the partnership. In 2010, the mission budget represented 57% (16.1/28.1 M€) of the total Nikhef partnership turnover. In 2016, this decreased to 41% (16.4/39.5 M€) and in 2022 it has further decreased to 36% (17.8/49.3 M€). If we compare the mission budget to the contribution of the university partners, then the ratios are even more dramatic: in 2010, the mission budget was 4,8 times higher than the university contributions (16.1: 3.3 M€); in 2016 this dropped to 2.4 (16.4 : 6.8 M€) and further in 2022 to 1.3 (17.8 : 13.5 M€). This makes it increasingly difficult for the Nikhef Institute to continue to fulfil its nexus role, whereas this role is indispensable to establish a coherent and national science programme with international success.

Therefore, Nikhef foresees the need for a structural increase of its mission budget with at least 1 M€ annually.



Large hadron collider (LHC) at CERN, Geneva.

APPENDIX 06

A. ELABORATION OF THE STRATEGY PER PROGRAMME

Where in the previous chapters the *integral* Nikhef strategy has been set out, in this appendix the strategies of Nikhef's eleven research programmes are presented in the form of a mission, goals for the coming six years and actual strategy to achieve these goals.

6.1 THEORY

MISSION

To conduct theoretical particle physics research with a broad spectrum of topics, ranging from collider physics and QCD, the structure of the proton, flavour and neutrino physics to astroparticle physics and cosmology. The theory group serves as a national centre for particle physics phenomenology and keeps strong links with the Nikhef experimental programme and other Dutch and international theoretical physics groups.

Goals

- → Perform high-precision calculations for searches of physics beyond the Standard Model.
- → Understand and interpret anomalies in the current data.
- → Develop the theoretical framework for precision tests of the Standard Model and new BSM searches at the HL-LHC and future colliders and experiments.
- → Explore new directions in neutrino and astroparticle physics and cosmology.
- → Pursue theoretical physics applications of artificial intelligence and quantum computing.

Strategy

The Standard Model of particle physics has emerged from a strong interplay between theory and experiment, starting in the 1960s. It has turned out to be an extremely successful framework to describe the electroweak and strong interactions of elementary particles. The final ingredient – the Higgs boson – was observed by ATLAS and CMS in 2012. Apart from tensions in data for certain rare B-decay processes and the anomalous magnetic moment of the muon, the Standard Model was impressively confirmed by experiment. However, we have indications that the Standard Model cannot be complete, where the baryon asymmetry of the universe is a key example. At the high-energy frontier given by the LHC, no signals for physics beyond the Standard Model have been found so far.

In this era of particle physics, high-precision studies are in the spotlight as they may finally reveal imprints of physics from beyond the Standard Model. Here, the goal is to perform Standard Model calculations with highest precision and to identify the most promising processes and observables for experimental studies. Discrepancies between the Standard Model calculations and measurements would reveal the presence of new interactions and particles, which could have masses far too heavy to be directly produced at the LHC.

This "stress-testing" of the Standard Model is a key element of the theoretical physics programme. The further exploration of the Higgs particle plays a central role, with questions about its self-couplings and whether there is an extended scalar sector. Cutting-edge QCD calculations are another part of the collider physics programme, as well as studies of the substructure of the proton, addressing exciting features such as "intrinsic charm". In pursuing these studies, links with the experimental ATLAS program are utilised and will be further developed in the future.

The flavour sector, which describes interactions between different quark and lepton "flavours", i.e. species of these particles, plays another outstanding role for testing the Standard Model with unprecedented precision. Anomalies in data for strongly suppressed B decays originating from quantum fluctuations indicate new particles and interactions, where the possibility of the violation of lepton flavour universality – a key feature of the Standard Model – is a particularly exciting and surprising option. Further studies are related to imprints of new sources of CP violation, in particular in B-meson decays. The theory group is at the forefront of the corresponding theoretical analyses and keeps strong links with physicists from the LHCb programme. In the lepton sector, the anomalous magnetic moment of the muon shows a long-standing puzzle. It may be linked to the rare B-decay anomalies and electric dipole moments. These flavour probes are also part of the theoretical physics strategy, with a link to the eEDM programme at the VSI/RUG.

The nature of neutrinos and their role for the baryon asymmetry of the universe, CP violation in the neutrino sector and the question of whether dark matter has a particle explanation are further research lines, as well as explorations of axions and "invisible" particles. Here links to the APP/neutrino/multimessenger programme, including also calculations of interactions of cosmic rays with the atmosphere of the earth at highest energies, are established. The theory group is furthermore interested in cosmology, addressing topics ranging from Higgs inflation and the electroweak phase transition to the matter-antimatter asymmetry. Gravitational waves are also part of this research line, with the goal to further utilise and develop links with the experimental programme.

Nikhef theoreticians at work.

In exploring these topics, we can build upon our world-class expertise in QCD, flavour physics and effective field theories. Moreover, the theory group maintains a strong network with the broad Dutch theoretical physics community, with regular meetings and various activities, involving also strongly the training of PhD candidates and junior physicists. Moreover, the theory group has lively interactions with the Nikhef experimental programme, which is reflected by activities such as "Theory Meets Experiment" mini-workshops, and joint papers and PhD projects. The further exploitation and development of these synergies will offer exciting new opportunities for Nikhef, thereby also further strengthening the role of the Nikhef theory group as the Dutch centre for particle physics phenomenology. Here, focus is on confronting theoretical considerations and predictions with experimental observations. Threats for the implementation of the programme are given by the funding situation, with limited NWO-I theoretical physics staff positions.

The longer-term ambitions for 2023-2028 and beyond depend strongly on results from the (HL)-LHC and other HEP/APP experiments: should New Physics be found, its nature would have to be clarified and a theoretical description to be developed. In case New Physics cannot (yet) be established, the high-precision programme at the LHC would have to be fully exploited, identifying the most promising research directions to find New Physics. In this context, the theoretical physics programme will also be linked with the Nikhef and European/CERN discussions about future colliders, such as the FCC and muon colliders, and future experimental facilities. Applications of artificial intelligence and quantum computing, such as for Monte Carlo simulations, will also be explored. For all possible paths, a rich and broad theoretical particle physics program will be crucial.

6.2 ATLAS

MISSION

To deepen our understanding of fundamental physics at the smallest distance scales accessible at the Large Hadron Collider. To uncover signs of physics beyond the Standard Model through study of Higgs boson, top quarks, vector bosons interactions, or through direct observation of anomalies.

Goals

- → Measure properties of the Higgs boson, top quarks and vector bosons, with particular focus on production in extreme kinematic regimes. Search for additional Higgs decay modes not yet observed.
- → Develop model-agnostic data-driven searches for signs of new physics based on recent advancements in machine learning techniques.
- → Create a unified programme of precision measurements for Higgs, top-quark and vector boson properties that can be coherently and jointly interpreted.
- → Construct and install ATLAS detectors: the Inner Tracker end-cap strip detector, the High Granularity Timing Detector; upgrade the full ATLAS TDAQ system to FELIX, upgrade the muon system electronics. Start R&D towards detector upgrades beyond 2028.
- → Intensify our long-term R&D programme on track reconstruction, muon identification, flavour tagging and performance studies to strengthen the run-3 physics results in the short term, and to meet the challenges of the HL-LHC with a completely new inner tracking detector in the long term.

Strategy

The aim of the ATLAS programme is to unravel the outstanding questions on our understanding of Nature. Open questions include: What is the origin of mass for elementary particles? Are there new symmetries, new physical laws? What explains the patterns we see in the SM? What is dark matter? Does it affect observable LHC physics? To answer these and more questions, we aim for a three-pronged strategy that comprises the study of selected high-p_T physics processes, the construction and installation of new detectors, and the development and deployment of new data analysis methods.

The Higgs boson remains the least precisely tested part of the Standard Model to date, despite the order-of-magnitude improvements in measurements of its properties in Run-2. Given its multiple important roles in the SM, the Higgs boson will remain the most fertile hunting ground for finding signs of new physics in LHC data, with many fundamental questions on the nature of the Higgs boson remaining unanswered today. Study of the Higgs boson will therefore remain the largest group research effort, with a focus on three areas: i) Discovery and measurement of properties of rare Higgs decays, ii) Development of new strategies for precision studies of abundant Higgs decays that leverage differential information on both the Higgs production and decay side, and iii) Study of Higgs-boson self-couplings, and hence of the Higgs potential, via measurements of single Higgs and di-Higgs production.

In parallel to the Higgs programme, we will investigate di-boson production and top-quark production. Study of di-boson production probes rare 3- and 4-boson interactions at high energies as well as specific Higgs-mediated interactions, which have a crucial role in the SM to retain its unitarity at high energies. All these interactions can be tested with unprecedented precision in Run-3. The top-quark remains the most massive elementary particle discovered to date, and often has a special role in new physics theories for that reason. Precision studies of top quark properties is thus of great importance. We aim to use the abundance of Run-2 and 3 top-quark data to study a broad range of processes ranging from abundant pair production to ultra-rare decays. Finally, we will continue searches for direct signs of new physics to complement our measurement-based program to find new physics, focusing mostly on data-driven model-agnostic strategies driven by recent advances in machine learning techniques.

There is a clear synergy in development of data reconstruction and analysis methodology for all aforementioned measurements. Each exhibits a strongly enhanced sensitivity to new physics in their highest p_T regimes, and all critically depend on high-quality object identification, in particular of flavoured particle jets. With a strong group expertise and continuing efforts in machine learning, flavour tagging, track reconstruction, muon reconstruction and statistical modelling, we aim to make advances in precision across the full range of measurements beyond the statistical power brought by LHC run-3.

Given the interwoven nature of diboson, top quark and Higgs measurements, a global analysis strategy that emphasises coherent modelling of both systematic uncertainties and the parametric form of allowed deviations from the SM across all measurements will be crucial for the accuracy of future results. We aim to exploit the rapid advances in the development of SM Effectively Field Theory to realise a unified, coherent measurement program in top-quark, Higgs and diboson physics. Performing and applying this joint analysis at the experiment level allows specifically to tailor and optimise the individual measurements to construct a combination with better statistical sensitivity and smaller systematic uncertainties.

Detector development and construction strategy

Multiple detector systems require significant upgrades or replacements to prepare the ATLAS experiment for data taking in the HL-LHC era, starting in 2029. We are responsible for several of these upgrades: the assembly and commissioning of a completely new all-silicon end-cap of the Inner Tracker; the upgrade of the full ATLAS TDAQ system to the FELIX system, co-developed by Nikhef; the timing calibration as well as the FELIX-based readout of the new High-Granularity Timing Detector (HGTD); and the upgrade of the muon system electronics. The bulk of the construction

Preparing the ITK endcap for ATLAS.

activities will take place in parallel to Run-3, with installation and commissioning foreseen in 2026-2028. With the newly installed detectors, the ATLAS experiment will be able to analyse events with up to 200 superimposed pp collisions, and handle the corresponding data rates. We will already shift focus in our track reconstruction expertise in the period 2023-2028 towards HL-LHC tracking, as computational efficiency in the high-density environment of the HL-LHC requires significant advances in methodology to fit in the computational budget. Connected to our new commitment to the HGTD, we will also strengthen our efforts in R&D of tracking sensor technology capable of fast timing, preparing for future upgrades of detectors beyond 2029, as well as novel track reconstruction algorithms with emphasis on hardware acceleration and machine learning to help meet the demands of the HL-LHC era.

In 2029, the era of high-luminosity running of the LHC starts, culminating in a 10-fold increase of the data sample w.r.t. that of run 1-3. We aim for a high-p_T physics programme that is focused on the very highest energy collisions of the LHC, which represent the most sensitive probe to new physics. In particular, the increased angular coverage of the new Inner Tracker in the forward direction will increase the acceptance for all vector-boson fusion processes, which generates a large fraction of all high-p_T collisions. A central part in this programme will be a Higgs precision physics programme in a broad range of signatures, in addition to a focused effort on observation of Higgs self-couplings.

In parallel, we plan a significant continued effort in detector development and construction. The initial HGTD, installed in 2028, will need new sensors after three years of running, and it is our ambition to participate in sensor development and deployment of these in Run-5. On the longer term, after six years, also the inner layers of the pixel barrel tracker will need to be replaced, presenting an opportunity to also install a layer of new sensors with fast-timing capabilities in the central tracking regime. The combined requirements for such sensors in this regime exceed those of currently available technology and we aim to participate in the R&D effort in the decade leading up to their deployment.

6.3 LHCB

MISSION

To understand the origin of the matter-antimatter imbalance in the universe and to detect signals of physics beyond the Standard Model through quantum fluctuations. To develop and implement state of the art technology for particle detection and for cutting edge heterogeneous computing systems and algorithms.

Goals

- → Finalise commissioning of the LHCb upgrade-1 detector subsystems Velo, SciFi and RTA. After the construction and installation of the Velo and SciFi sub-detectors and the implementation of the RTA framework, new alignment, optimisation and monitoring tasks will be implemented to allow full exploitation of the data-taking process.
- → Perform precision measurements on decay-time dependent CP violating phenomena, in particular exploiting the flavour oscillations of the Bs-meson. Focus will be on the measurements of the CKM decay phase angle γ, and the mixing phase φs.
- → Analyse (very) rare decay b-decays to probe for virtual particles at very high mass scales. The rare b-decay modes include electrons in the final state and focus on angular analyses, as well as decays of the Bc→τν where the Bc particle is directly observed in the detector. The very rare decay modes serve to measure the ratio of Bd →μ+μ- over Bs→μ+μ- and finally search for the elusive mode Bs→e+e-.
- → Develop novel fast-timing pixel sensors and corresponding electronics for the LHCb upgrade-II vertex tracker. The R&D focusses on hybrid pixel sensors, fast electronics as well as on design and construction of modules. In addition to cross-programme work at Nikhef (FASTER), we will exploit collaboration with industry on electronics, in particular related to TimePix4 applications.
- → Introduce the next level of heterogeneous computing into the LHCb online and offline computing systems. The aim is to work towards the concept of real-time 4D tracking, exploiting spatial and temporal resolution of new detectors as well as performance of new computing architectures. The medium-term goal is to introduce GPU-based algorithms into HLT-2 and to investigate the possibility of a distributed trigger. The longer-term goal is to do R&D on the feasibility to apply quantum computing in tracking algorithms.

Strategy

Flavour-physics experiments are an excellent testing ground to investigate some of the most fundamental open questions in particle physics by means of so-called indirect searches. The reach of new physics scales probed by indirect searches of LHCb, the so-called precision frontier, is complementary to that of direct searches of Atlas and CMS. The importance of a long-term flavour-physics programme is also recognised in the update of the European Strategy for Particle Physics.

At Nikhef, our group activities gravitate around our expertise: charged particle detection and physics of unstable meson decays into charged particle final states. We have a long track record of state-of-the-art tracking detector design, construction and commissioning, as well as real-time particle reconstruction. Particular examples of top-notch technology are the RF box, the Velo Pixel sensors located 5mm from the LHC beams, the high-rate VeloPix chip, and last but not least the construction of the first large-surface scintillating fibre tracker. The latter includes silicon photomultiplier readouts at deep sub-zero temperatures.

At the same time, we designed and are currently commissioning the GPU-based Allen software framework, implementing track finding and track fitting algorithms providing full event reconstruction in real time at 30 MHz.

Remote engineering support for the LHCb VELO installation.

We have unique expertise in the reconstruction of electrons, which is notoriously difficult due to Bremsstrahlung in the detector material of the spectrometer. As a particular example, we have implemented a novel real-time electron reconstruction algorithm that doubles the efficiency of electron detection. For the longer term we focus on the concept of 4D-tracking, exploiting the excellent spatial and temporal resolution of new fast-timing sensors.

The physics analyses in our group build on our expertise of charged particle reconstruction. Our group has led the work of decay time-dependent CP-violation analyses: Bs→Ds π events, measurements of the CKM angle γ with Bs→Ds K events, as well as the angle φs with Bs→J/ψφ events. Subsequently we provided key contributions to the measurement of the very rare, so-called "smoking gun" decays Bs→μ+μ-, while we are currently also pioneering the search for the even rarer decay: Bs→e+e-. The so-called "flavour anomalies" are a hot topic in our physics programme and our group leads the angular decay distribution analyses on Bd→K*e+e- decays, relying heavily on, and profiting from, our expertise in electron reconstruction.

The LHCb group is a homogeneous team involving researchers from Nikhef, VU, RUG and UM. In addition, we have collaborations with the Nikhef theory group on physics analysis, with the R&D group on fast timing detection sensors, and the Nikhef PDP and UM DACS departments for research and implementations of heterogeneous computing. We try to push the high-intensity computing frontier by implementing world-record-throughput GPU algorithms and we are studying the feasibility of quantum computing for track reconstruction in a very high-density particle environment. For the latter we have established a collaboration between UM and IBM Zurich research laboratories.

Concerning data throughput, we are exploring collaborations with the M4I company in Maastricht which has an application for the TimePix chip for image scanning.

The above summarises the activities of an enthusiastic and highly motivated LHCb group, which looks forward to an exciting data taking period in Run-3 and Run-4 at the precision frontier, and a very challenging and stimulating technology development for a novel LHCb detector to be installed in the long shutdown "LS4".

6.4 ALICE

MISSION

To understand the multi-body dynamics of the quarks and gluons of the strong interaction, and in particular how they give rise to the properties of the high-temperature phase of QCD, the quark-gluon plasma (QGP).

Goals

- → Understand the effect of coherence effects in interactions of high-momentum quarks and gluons with the QGP through measurements of jet substructure and energy loss as a function of jet size.
- → Determine the spatial diffusion coefficient of heavy quarks from azimuthal distributions of charm and beauty hadrons.
- → Improve our understanding of hadron formation in hadronic collisions via measurements of strange and charm baryon production and correlations between strange baryons and mesons.
- → Use the magnetic field in non-central heavy-ion collisions to constrain the electrical conductivity of the medium to search for parity-violating effects in the strong interaction and study the vortical structure of the QGP.
- → Develop a next-generation integrated silicon sensor that provides a time resolution of 20 ps or better for particle identification in the future ALICE 3 experiment.

Strategy

Heavy-ion collisions at the Large Hadron Collider (LHC) offer a unique opportunity to study the QGP in the laboratory. The upgrades that have been installed in the ALICE detector during Long Shutdown 2 (2019-2021) provide improved pointing resolution while also allowing us to collect data samples that are up to 100x larger than in Run 1 and 2. These improvements provide opportunities to significantly enhance our understanding of the properties of the QGP produced at the LHC.

Measurements of transport coefficients provide key insights in the microscopic dynamics of quarks and gluons in the QGP. For example, the energy loss of high-energy quarks and gluons that propagate through the plasma depends on the temperature and mean-free path in the plasma. These quarks and gluons radiate and split as they propagate, giving rise to parton showers which are detected as jets in the experiment. Measurements of angular substructure of these jets are being pursued to provide information on the screening length in the plasma through coherence effects. Similarly, the interactions of heavy quarks with the QGP can be described as a diffusion process, where the diffusion coefficient depends on the mean-free path and on residual interactions between the light quarks in the plasma. To determine the diffusion coefficient of heavy quarks, high-precision measurements of the azimuthal asymmetry of charm and beauty hadrons are planned with the new data from Run 3.

To test our understanding, the measured properties of the QGP have to be confronted with theoretical expectations. For this we collaborate closely with the theory departments at Utrecht University and at Nikhef. A direct measurement of the temperature of the QGP and its time evolution is essential for a detailed comparison with theory. This information is provided by measurements of electromagnetic radiation, of both photons and electron-positron pairs. These measurements are challenging due to the very large background of photons and electrons from hadronic decays. With the upgraded detector, the precision that is required to determine the temperature is in reach.

Testing sensor staves for ALICE.

In non-central heavy-ion collisions, an extremely large magnetic field (10^{15} T) is produced by the passage of the charged nuclei. This field produces a charge-separation of particles and high-precision measurements of this effect will allow us to determine the average magnetic field which constrains the electrical conductivity of the QGP. Moreover, the large magnetic fields may give rise to charge separation due to as-yet-undiscovered parity-violating effects in QCD.

Analyses to search for this effect in the heavy-ion collisions are also planned with the new high-statistics data samples. Non-central heavy-ion collisions also have a very large angular momentum, which leads to vortical flow that ultimately produces polarisation of the produced particles. Analysis of these signals provide insight in the coupling between intrinsic angular momentum of the constituents and the global angular momentum in a quantum fluid.

R&D for future detectors

Beyond run 3 and 4, the heavy-ion programme at the LHC aims to determine the time evolution of the temperature of the QGP with differential measurements of di-lepton emission as a function of mass, pT and azimuthal angle and to understand the processes that drive partonic matter to equilibrium by mapping out the mass dependence of the diffusion coefficient and by measuring the abundances of multiply-charmed baryons and exotic hadrons in heavy-ion collisions. This programme requires the development of next-generation instrumentation, such as integrated silicon particle sensors that provide time resolution in the 20 ps range. Nikhef is involved in R&D for such sensors in conjunction with similar development for the other LHC experiments.

6.5

ELECTRON-EDM

MISSION

To perform low-energy precision measurements on small quantum systems to explore the limits of the Standard Model of particle physics. Specifically, we use molecules to probe the electron's electric dipole moment (eEDM). We aim to increase the sensitivity for new physics through the combined effort of theory and experiment.

Goals

- → Publish a value of sensitivity to the eEDM using a fast beam of BaF molecules, demonstrating the working system of our approach (completing phase 1). We aim for a sensitivity of 10-27 e.cm, based on the 600 m/s molecular beam and our improved understanding of systematic effects.
- → Demonstrate a bright, slow and transversely cold beam of BaF molecules for eEDM measurements (towards phase 2 measurement).
- → Publish a second value of sensitivity to the eEDM using a slow beam of BaF molecules, with increased sensitivity (phase 2 measurement). We foresee two phases: a) using the laser-cooled 200 m/s cryogenic beam, aiming for 5x10-29 e.cm, and b) using the decelerated 30 m/s beam, aiming for 5x10-30 e.cm. We will use pumping of rotational and vibrational states to increase the intensity, and are preparing a high-voltage upgrade for the molecule decelerator.
- → Develop an effective-field theory framework to interpret the BaF eEDM limits in terms of fundamental CP-violating operators.
- → Demonstrate suitability of selected polyatomic molecules for future eEDM measurements using interaction times > 100 ms (towards phase 3 measurement).

eEDM group in the Groningen lab.

Strategy

We envision three phases in our eEDM programme, stepwise increasing the sensitivity of our low-energy precision measurements:

- Phase 1 will be completed in 2023 with the publication of a first limit on the electron-EDM using a fast beam of BaF molecules. At that point our experiment will be relocated to a new building to the Zernike Campus in Groningen.
- Phase 2 is foreseen to increase the sensitivity to the eEDM by using a bright, slow and cold beam of BaF molecules. We will work towards this goal in the period 2023-2028 by integrating our slow beam with the eEDM measurement setup. In parallel we will prepare for phase 3 of the eEDM programme.
- Phase 3 will involve further increasing the coherent interaction time with the molecules, and thereby the sensitivity to the eEDM. The optimal route towards this goal will be explored by developing suitable traps for molecules and creating a molecular fountain. The close integration of experiment and quantum chemistry calculations in this phase is central to our approach.

The close integration of experiment and quantum chemistry calculations in this phase is central to our approach. In the context of the foreseen increase in eEDM sensitivity in our experiments as well as others worldwide (currently the best limit is at $2x10^{-30}$ e.cm), we will develop an effective field theory framework to interpret the eEDM results in terms of fundamental CP-violating parameters. With this, we will clarify and highlight the connection between low-energy precision experiments and the observables from high-energy experiments.

Looking beyond 2028, we foresee the implementation of the above-mentioned phase 3 of our programme. Beyond that, the final frontier is to make optimal use of collective quantum enhancement techniques such as spin squeezing. To demonstrate this would be a breakthrough in the field of low-energy quantum sensing of new physics.

6.6 NEUTRINO PHYSICS - KM3NET

MISSION

To study the properties of neutrinos and identify high-energy neutrino sources in the universe. To establish the neutrino mass ordering, search for CP-violation in neutrinos and search for beyond-the-standard model physics. To study permanent and transient cosmic neutrino sources and their particle acceleration mechanisms in a multi-messenger context.

Goals

- To complete the construction of the KM3NeT-2.0 detector.
- To determine the neutrino mass ordering and neutrino oscillation parameters.
- To detect sources of high-energy cosmic neutrinos and study them.
- To prepare for DUNE operation and data analysis, with emphasis on long-baseline oscillations and CP-violation in the neutrino sector.
- To search for neutrinos from dark matter annihilation or decay, and signs of beyond-the-standard model physics in neutrinos.

Strategy

The neutrino physics group studies atmospheric and cosmic neutrinos with the KM3NeT infrastructure, and prepares for analysis of future data of the DUNE experiment currently under construction.

The large contribution of Nikhef in the KM3NeT detector production will be continued and the available experience will be further exploited for future DOM/DU productions. The Nikhef neutrino group also builds on its large heritage in neutrino telescope event triggering, reconstruction and analysis and will continue to play a major role in the KM3NeT collaboration in this. It also benefits from the strong computing support within Nikhef to pursue its goals with state-of-the-art methods (e.g. grid computing, machine learning).

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) is used to make detailed studies of 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. KM3NeT/ORCA will allow for the mass ordering to be established in about 4 years of operation, depending on the value of the mixing angle and the ordering itself. In addition, KM3NeT/ORCA will make a precise measurement of and study the unitarity of the mixing matrix, and search for BSM physics including neutrino decay and non-standard interactions.

The discovery of a flux of very-high-energy cosmic neutrinos by the IceCube experiment in 2013 has triggered a revolution in the field of astroparticle physics. 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 this field. Candidates include spectacular objects like blazars, starburst galaxies, radio galaxies and (galactic) supernova remnants. The sparsely instrumented section of the KM3NeT infrastructure, KM3NeT/ARCA, is expected to make a rapid independent 5-sigma confirmation of the IceCube diffuse cosmic signal, and, due to its superior pointing resolution, is in an excellent position to identify neutrino sources. KM3NeT aims to contribute to multi-messenger studies of high-energy sources by adding neutrino information to electromagnetic observations, gravitational wave signals and charged cosmic ray measurements, and is able to issue fast alerts of transients in a large part of the sky. Cosmic neutrinos also offer a way to study properties of neutrinos themselves, at energy scales and over distances unattainable using earth-based neutrino beams, and thereby to search for BSM physics. Cosmic neutrinos may also result from the decay or annihilation of dark matter particles, and KM3NeT will search for an excess of neutrino events that could be a sign for such a process. KM3NeT also aims to detect neutrinos from a galactic supernova explosion, should one occur in the next years, and is able to contribute to cosmic ray physics by measuring, in the deep sea, the high-energy muon component of cosmic-ray induced air showers.

To realise the ambitions, it is important to complete KM3NeT-2.0 as soon as possible. In parallel, we carry out R&D on detector upgrades, including the study of high-quantum-efficiency PMTs, and investigate acoustic detection of ultra-high-energy neutrinos with a new generation of hydrophones.

KM3NeT deployment hardware onshore in Toulon.

The LBNF/DUNE experiment is under construction in the USA, and will consist of a high-intensity neutrino beam generated at Fermilab (Chicago), a Near Detector at Fermilab, and a Far Detector at the Sanford Underground Research Facility in Lead, South Dakota, 1300 km downstream from the neutrino source. DUNE aims to search for CP violation in neutrinos and measure the CP-violating phase in the PMNS mixing matrix to 10-degrees accuracy, and make accurate measurements of neutrino oscillation parameters and the neutrino mass ordering. It will also search for anomalous tau neutrino appearance, non-standard interactions, sterile neutrinos, proton decay and supernova neutrinos. The Near Detector will allow for electroweak physics research using a very large data sample. The Far Detector will consist of very large Liquid Argon Time Projection Chamber modules, at unprecedented scale. As part of the CERN neutrino platform, protoDUNE at CERN serves to prototype this technology, with data from atmospheric muons and the SPS test beam. The ambition of Nikhef in DUNE is to improve event reconstruction of neutrino events, starting with protoDUNE, develop methods for better photon detection, and contribute to DUNE computing.

The capabilities of neutrino oscillation detectors, and in particular KM3NeT/ORCA, would be significantly enhanced with the novel concept of a tagged neutrino beam, where individual detected neutrino events are traced back to individual neutrino production events at the source, thus unambiguously establishing type and kinematics of the original neutrino.

KM3NeT aims to be a “green” facility with minimal carbon footprint. It also intends to make its data publicly available for Open Science purposes.

6.7 DARK MATTER

MISSION

To identify particle dark matter and to study rare astroparticle physics processes.

Goals

- → Successfully operate and analyse data from XENONnT and play a leading role in the search for dark matter signals in the data.
- → Exploit the XENONnT data to its fullest by developing new dark matter analysis techniques to search for low-mass dark matter, axions and other potential signals.
- → Use the extraordinarily low background of XENONnT to measure rare radioactive decays such as double-electron capture, two-neutrino double beta decay and beta decay itself to better understand weak interactions in the nucleus.
- → Prepare for the next-generation liquid xenon observatory for dark matter and neutrino physics, DARWIN/XLZD. Our goal is to be a major player in the design and construction of the experiment, using the strengths of Nikhef and our group.
- → Perform R&D for future potentially high-impact experiments to understand particle dark matter, neutrino properties and the cosmic neutrino background.

Strategy

The nature of dark matter and properties of neutrinos are among the most central issues in contemporary particle physics. The dual-phase xenon time-projection chamber (TPC) is the leading technology to study WIMP dark matter, while featuring substantial sensitivity to many alternative dark matter candidates. The XENON collaboration has operated a series of increasingly more sensitive xenon TPCs over the past two decades. The latest detector, XENONnT, contains 8.5 tons of xenon while the background level is about ten times lower than that of its predecessor, XENON1T.

XENONnT was commissioned in 2021 and results from the first science run of 100 days, about 1 ton-year of exposure, were recently published. Over a run-time of five years, the experiment is projected to collect about 20 ton-year of exposure in total, leading to a WIMP-nucleon spin-independent sensitivity of 1.4×10^{-48} cm^2 for a 50 GeV/c^2 WIMP mass at 90% C.L. The Nikhef Dark Matter group is planning to participate in the analysis of the upcoming data and extend the search to a broader range of dark matter candidates. We are particularly interested in exploiting the low-energy threshold achieved in this detector to search for low-mass WIMPs and axion-like-particles.

The very low radioactive background also allows for the study of extremely rare radioactive processes. The holy grail is an observation of neutrinoless double beta decay ($0\nu2\beta$) -- the only practical laboratory technique to determine if a neutrino is a Majorana particle. Almost 10% of the natural xenon in XENONnT is the $0\nu2\beta$-decay candidate ^{136}Xe. While XENONnT will not yet be competitive with present world-leading limits, it will allow us to develop the analysis techniques required for the future DARWIN/XLZD observatory to reach competitive sensitivities. Studies of other beta decays, such as a detailed measurement of the two-neutrino double

Preparing the PMT array at XENONnT, Gran Sasso.

beta (2ν2β) spectrum, double-electron capture in ^{124}Xe, and single beta decays in specific isotopes, may inform us on various nuclear physics aspects that are also essential in the interpretation of 0ν2β results.

The LZ and the DARWIN/XENON collaborations, operating the two most sensitive liquid xenon detectors, recently decided to join forces as the XLZD consortium to build the next-generation liquid xenon observatory. The first science goal of the DARWIN/XLZD experiment is to probe the remainder of the WIMP parameter space after LZ and XENONnT finish data taking, down to the neutrino fog. This would require a detector of about 50 tons of natural xenon. This leads to the second science goal: the large amount of ^{136}Xe in this detector, the xenon self-shielding and a further reduction of backgrounds will make DARWIN/XLZD a very competitive 0ν2β experiment with a sensitivity to probe all the neutrino inverted mass hierarchy in the effective neutrino Majorana mass. The combination of large xenon mass and extremely low radioactive backgrounds will make this experiment a true multi-purpose observatory: it will not only probe dark matter models and neutrinoless double beta decay, but also measure solar neutrinos and neutrinos from other astrophysical sources. Construction of DARWIN/XLZD is not expected to start before 2026. The Nikhef group wants to be a major player in this experiment and has ambitions in leading the design and construction of the experiment.

Finally, we operate various small-scale R&D setups to study xenon properties and detector readout (XAMS), the fluorescence and optical properties of materials (VULCAN), and Cyclotron Radiation Emission Spectroscopy (PTOLEMY), and we plan to continue doing so. In recent years, various new quantum sensing techniques have become accessible in the lab. We think that some of them hold great promise for future astroparticle physics experiments and perhaps even beyond.

6.8 COSMIC RAYS

MISSION

To design, create and use detectors that measure air showers induced by ultrahigh-energy charged and neutral messengers from space and analyse this data to learn more about their nature, sources, acceleration mechanisms and fundamental interactions beyond the reach of accelerators.

Goals

- → Finish the installation of AugerPrime, including the radio detector.
- → Analyse AugerPrime data:
  - Combine radio with particle information at Auger to test the hadronic interaction models and obtain better information on the nature of primary cosmic rays.
  - Perform a combined analysis of all Auger data to obtain a better handle on the sources of UHECR.
- → Run GRAND prototype set-ups in Argentina, France and China and establish a location for a large GRAND hotspot.
- → Develop a next generation of low-power electronics for radio detection up to 200 MHz.
- → Develop a design for a GCOS detector unit and create a prototype.

Strategy

AugerPrime

The AugerPrime detector is an upgrade of the Pierre Auger Observatory. The base design particle detector consisted of a large Water Cherenkov Detector (WCD), enhanced with a scintillator detector (SSD) and faster electronics. Together, they allow for a better identification of secondary particles at ground-level (electron/muon separation) for vertically (with zenith angles up to about 60 degrees) incoming cosmic rays. This electron/muon separation will in turn provide a new handle on the number of nucleons contained in the primary particle and possibilities to identify air showers generated by neutral particles, like photons and neutrinos. The Dutch groups have been leading in the design of the SSD and have built about 10% of the units. We aim to analyse its data and capitalise on our knowledge of this detector as well as the knowledge we have gained in analysing WCD data.

Using Radio Detection (RD) we have found a way to extend the mass-sensitivity of the Observatory to inclined showers (zenith angles starting at about 60 degrees). For these showers, the particles arriving at the surface are mainly muons, thus particle detection only is not able to provide an electron/muon ratio. However, for inclined showers, the radio footprint is very large, thus the radio signal can be used to extract the total amount of electromagnetic energy generated in the shower and the electron/muon ratio can be used to infer the type/mass of the incoming particle. We have designed and developed RD systems to be installed at each of the 1661 surface detector stations to register the radio signals. Mass production is ongoing and deployment is foreseen to be completed in 2023. We aim to use the experience we have gained in the past 15 years in pioneering RD, as well as our understanding of the RD, to fully utilise the potential of AugerPrime.

Preparing for the next generation

AugerPrime will provide more insight into the nature of ultra-high-energy (UHE) particles, and may reduce the uncertainty in pinpointing the sources of these particles by studying anisotropies in the arrival directions as a function of the “type/mass” of the primary particle. Furthermore, AugerPrime might be the first detector with enough sensitivity to detect UHE neutrinos.

To fully unravel the origin of UHE particles, understand the physics that produced them and experiment effectively with UHE particle collisions in the atmosphere, a much larger sample will be required than will be available by a decade of AugerPrime measurements. Excellent particle identification on the incoming cosmic particles will help to ultimately answer the fundamental question associated with these particles. It is therefore necessary to build new observatories that are orders of magnitude larger than AugerPrime and that are capable of ultra-high-energy particle identification.

In addition, only by collecting sufficient data on charged cosmic rays, UHE neutrinos and photons, thus creating a true multi-messenger observatory, a complete and robust picture can be obtained. A possible path towards the future at the UHE frontier has been recently outlined in several white papers. Our focus is on two future key projects: GRAND is a multi-messenger observatory with the aim to connect ultra-high-energy neutrino-astronomy to the detection of cosmic rays and UHE photons. This requires an enormous aperture due to a combination of the expected low flux of particles and (neutrino) detection efficiency. GCOS has the main purpose to conduct precision measurements of the particle type/mass, ultimately determining the rigidity (energy/charge) of each incoming cosmic ray, requiring hybrid measurements of air showers. Both next-generation experiments will provide complementary information needed to meet the goals of the UHE community in the next two decades. It is expected that GRAND and GCOS will take over the leading role of the Auger Observatory in exploring the UHE frontier in the mid 2030s.

Water tank detector at the Pierre Auger cosmic ray observatory, Argentina.

6.9 GRAVITATIONAL WAVES

MISSION

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

Goals

- → Upgrade Advanced Virgo and run jointly with Advanced LIGO providing observational data of unprecedented reach and pointing accuracy.
- → Study gravitational waves from compact binary mergers, and extract knowledge about black-hole and neutron star populations, their formation channels, the equation of state of neutron stars and the expansion rate of the universe.
- → Develop strategies to probe the nature of black holes and the fundamental physics of gravity and shed light on the nature of dark matter and dark energy.
- → Develop new data-analysis techniques and consolidate innovative instrumentation R&D for Virgo, ETpathfinder, ET and LISA.
- → Consolidate the Dutch co-leadership of the Einstein Telescope and prepare a strong bid for hosting the Einstein Telescope in Euregio Meuse-Rhine.

Strategy

Instruments

Advanced Virgo: Hosted by the European Gravitational Observatory (EGO), of which NWO-I/Nikhef recently became the third member, Advanced Virgo is the European state-of-the-art gravitational-wave observatory. Advanced Virgo operates in a coordinated way of alternating upgrade and observation periods, as part of an international network including also the two LIGO observatories in the USA and KAGRA in Japan. The next upgrades will include larger mirrors with lower-noise reflective coatings, the use of frequency-dependent squeezed light to reduce quantum noise, Newtonian noise cancellation and improved sensor-technology. Nikhef is deeply involved in various aspects of these upgrades, many of which have synergies with ET and can be seen as stepping stones towards the realisation of ET. In parallel optical simulations, in which Nikhef has an international leadership position, will increase the understanding of such complex machines as Advanced Virgo and Advanced LIGO and guide our upgrade choices. The upcoming five years will include the 4th and 5th observation run of Advanced Virgo and Advanced LIGO with the prospects of a 10-fold increase of the number of observed signals.

Einstein Telescope: The Einstein Telescope (ET) is an infrastructure project for a new class of gravitational-wave observatories and was selected for the 2021 ESFRI roadmap. ET will be an international underground facility containing 10 km long interferometers with mirrors cooled to cryogenic temperature. ET is planned to be operational for the period 2035-2085. With the ETpathfinder, a test facility for ET, constructed in Maastricht, Dutch researchers are spearheading a multitude of innovative technologies for ET. In parallel, there are strongly supported and cohesively coordinated efforts underway to compose a bid for hosting the ET in South Limburg, including studies of the underground and geology in the region and building up supporting economic and societal eco-systems.

LISA: The Laser Interferometer Space Antenna (LISA) is a European Space Agency mission designed to detect and accurately measure gravitational waves from astronomical sources, not accessible to observatories on Earth. The LISA concept has a constellation of three spacecrafts, arranged in an equilateral triangle with 2.5 million kilometres long arms flying along an Earth-like heliocentric orbit. Nikhef supports LISA through development of the quadrant photodetectors.

Long-term physics analysis strategy

The long-term physics analysis strategy within the Nikhef consortium focuses on fundamental physics, astrophysics, and cosmology with gravitational waves from coalescing binary compact objects (neutron stars and black holes).

One aim is to continue to play a leading role in tests of general relativity, with increased attention not only on the strong-field dynamics of space-time, but on the nature of the compact objects themselves. How certain can we be that the presumed black holes whose mergers we regularly detect really are the standard black holes of classical general relativity? Motivated by Hawking's information paradox, alternatives to black holes have been proposed which do not have a horizon (e.g. fuzzballs in string theory) and whose properties would leave an imprint on gravitational wave signals; with increased detector sensitivities these signatures may soon be within our reach. Additional science is likely to come from observations of lensed gravitational waves from binary black-hole mergers; this offers the only known way to localise such events in the universe, with implications for cosmology, binary black-hole formation channels, and the propagation and polarisation content of gravitational waves. Equally exciting is the prospect of seeing binary inspirals with residual eccentricity; here too, the additional physics will enable novel tests of general relativity, as well as elucidating the formation of binaries.

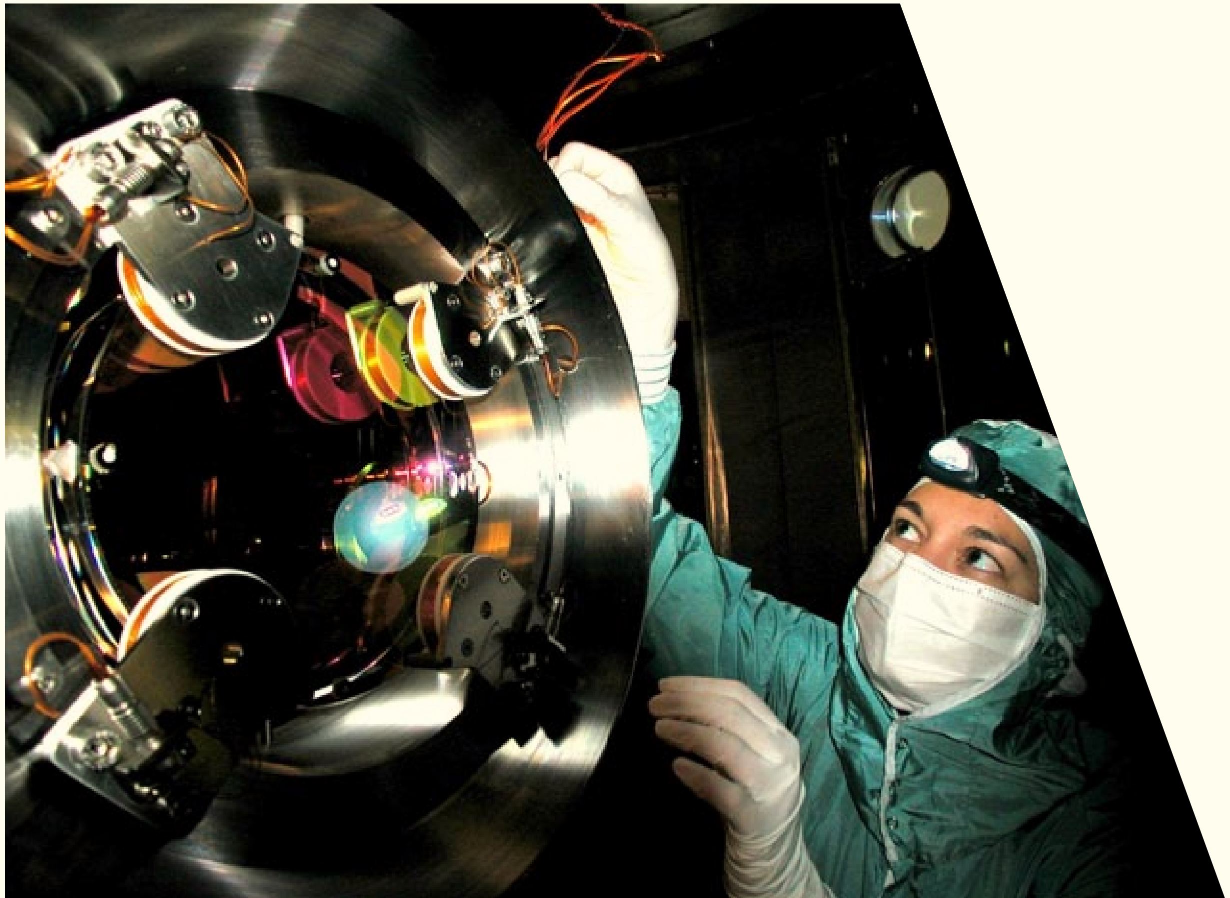
Researchers in the Netherlands are also well-positioned to help solve the problem of the neutron star equation of state, whose details remain a mystery. An opportunity (and challenge) that presents itself is to combine information from gravitational-wave observations of binary neutron-star mergers with electromagnetic data from the resulting gamma-ray burst and afterglow, as well as mass-radius measurements from NICER, and finally to connect these multi-messenger observations with what is seen in heavy-ion collisions at particle accelerators on Earth, e.g. the quark-gluon plasma that is studied by ALICE.

Gravitational-wave science also connects with the search for dark matter. Accumulations of dark-matter particles around binary black-holes will alter the orbital motion, which leaves an imprint upon the gravitational-wave signals; this way particle masses from less than a keV up to a GeV can in principle be probed. Alternatively, should dark matter consist of ultra-light bosons with a Compton wavelength comparable to the size of an astrophysical black-hole, then rotational kinetic-energy of the black hole can be converted into a boson cloud, which would again noticeably affect binary black-hole inspiral. The accessible boson-mass range is set by the sizes of the black holes that can be observed; in the era of Einstein Telescope and LISA a sensitivity between 10^{-19} and 10^{-10} eV can be reached.

Finally, binary inspirals are cosmic distance markers: with a network of gravitational-wave detectors the distance to the source can be inferred directly from the gravitational-wave signal. To do cosmology, the redshift is also needed. In the case of a binary neutron-star merger with an identifiable electromagnetic counterpart one can establish the redshift of the host galaxy. For binary black-hole mergers, information about the redshift can be obtained in a statistical fashion, by cross-correlating with a galaxy catalogue. The observation of the above-mentioned lensed gravitational waves, which can undergo significant magnification, will also enable cosmology at high redshifts. Using all these methods together, with gravitational waves we will be able to weigh in on an important new problem in cosmology: the Hubble constant tension.

Looking towards the longer-term future, ET and LISA will pose formidable data-analysis challenges related to the much larger number of detectable signals, the much longer time that the signals will be recorded, and the resulting problem of overlapping signals. These problems must be solved in advance of these new observatories being active, so that their scientific promise can be optimally exploited and computational expense can be kept under control. A variety of strategies will be developed, tested and compared, in which machine learning is likely to play an increasingly important role.

Mirror preperations at the Virgo gravitational wave detector, Italy.



6.10 DETECTOR R&D

MISSION

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

Goals

- Optimise Monolithic Active Pixel Sensors (MAPS) for improved timing resolution and radiation hardness.
- Develop new hybrid sensors, e.g. a 3D sensor with better spatial resolution, and explore the possibility of gain.
- Develop the LISA Quadrant Photoreceiver, a sensitive photon detector in a housing with high-precision alignment.
- Develop optimised photodiodes with reduced scattered light for Virgo, and for various laser wavelengths for ET.
- Develop a MEMS accelerometer with unprecedented sensitivity (few ng/sqrt(Hz)) integrated with low-noise CMOS readout electronics.
- Develop a phase camera with high frame rate, providing absolute phase information.
- Establish a facility to directly measure the thermal noise of samples with different coatings at cryogenic temperatures.

Strategy

The detector R&D group maintains links with many experimental Nikhef programmes regarding 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: the Medipix readout chip project has been running for over 20 years, for example, and has led to various spin-off activities.

Detector research also requires substantial resources, and fosters unconventional research by R&D staff members. Instrumentation grant proposals are often only awarded by funding agencies after initial seed investments by Nikhef. To stay at the forefront of technology, Nikhef invests in enabling technologies like CMOS chip design, MEMS fabrication, advanced optics, digital electronics, simulation tools and signal processing.

The strategy and planning 2023-2028 are focused towards two research tracks, in smart and fast pixels and in instrumentation for gravitational wave detectors, plus blue-sky R&D.

Smart and fast pixels

Revolutionary improvements in semiconductor detector performance are needed to match the requirements of future experiments, both for the planned tracker upgrades of the LHC experiments and collider experiments still on the drawing board. These instruments necessitate ultra-fast detectors, enabling 4D-tracking (three spatial dimensions plus time) to distinguish the multiple particle interactions occurring within a bunch crossing. Another challenge is to achieve unprecedented radiation hardness of these detectors. This research track concerns two distinct technologies: Monolithic Active Pixel Sensors (MAPS) and hybrid sensors. In MAPS, the sensor and readout electronics are integrated into one layer while they are separated in the hybrid type. It is essential to understand the nature of the limitations in sensor and readout electronics performance, both from first principles and related to the technology used for fabrication. In parallel, the group will focus on the design of fast-timing circuits in CMOS readout chips, like time-to-digital convertors, to cope with the fast sensor signals.

To advance the time resolution towards picoseconds, the interplay between characterisation and simulation is crucial. What we learn from tests with particle beams can be compared to simulations, and used to improve sensor structures. In the quest for ever faster sensors a variety of sensor concepts will be studied.

So-called 3D pixel sensors are intrinsically faster but the spatial resolution needs to improve by reducing the pitch (profiting from advancements in semiconductor processing) and by reading out both types of electrodes (i.e. double-sided readout). To reduce the material budget, thinner sensors are required but this reduces the amount of signal. Hence, gain structures in 3D sensors, which depend on geometry more than on doping level, will be explored. Another candidate is the Low-Gain Avalanche Detector (LGAD), where we exploit novel ideas such as trench isolation and an unsegmented gain layer on the opposite side of the sensor (inverted-

LGAD). MAPS are thin sensors by design and allow very small pixel sizes. The challenge is to make them fast and improve the radiation hardness.

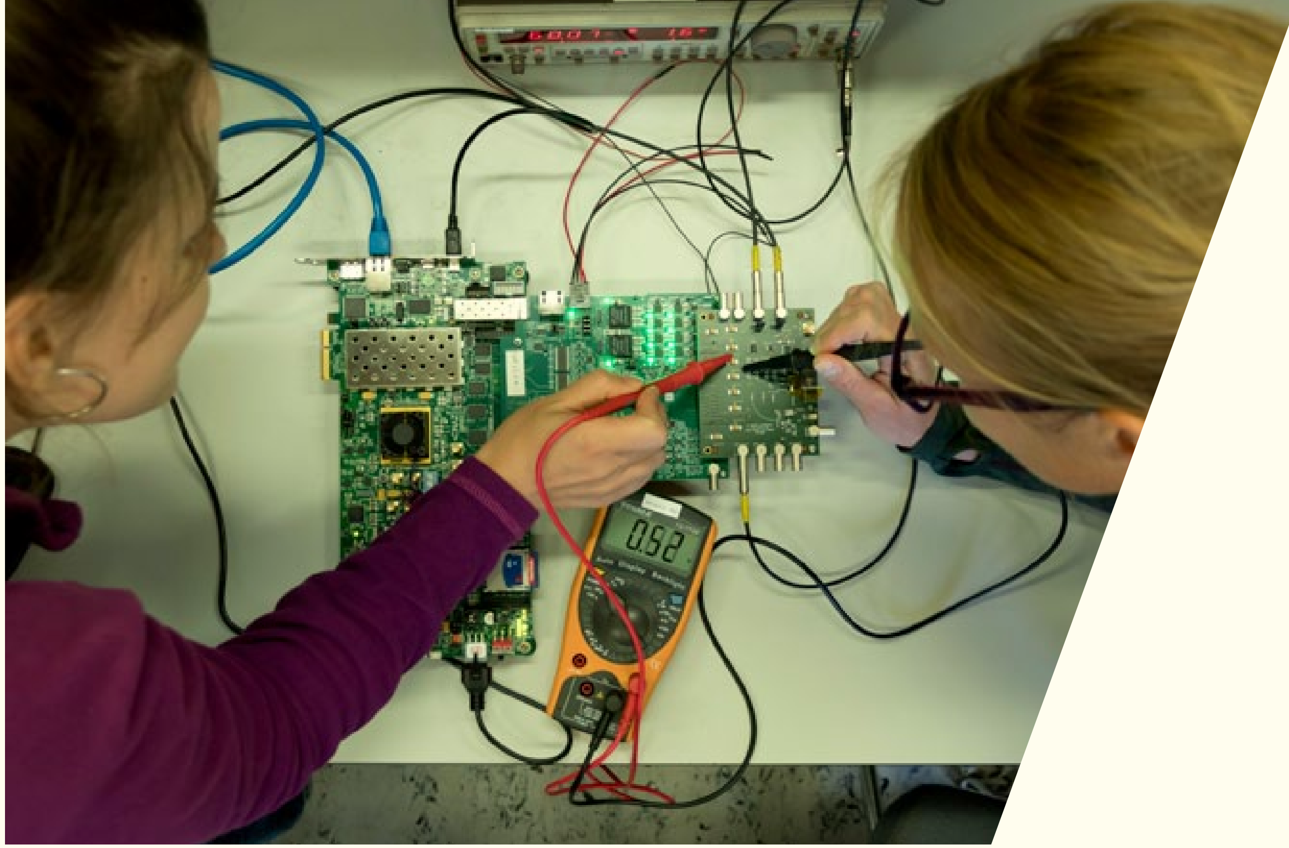
Instrumentation for gravitational wave detectors

Nikhef is deeply involved in instrumentation development for the next generation of gravitational wave detectors: the Earth-based Einstein Telescope (ET) and the complementary Laser Interferometer Space Antenna (LISA), a 2.5 million km-sized space instrument.

For Earth-based detectors, thermal noise is one of the noises currently limiting the sensitivity. One of the strategies proposed for ET is to cool the main mirrors, forcing research of new materials for the mirrors themselves and the coatings deposited on them. This requires the development of instrumentation to characterise materials at cryogenic temperatures. The goal is to design, implement and make available a facility for the GW collaboration, together with Twente University, to measure the thermal noise of coating samples directly. Another possibility to reduce the impact of thermal noise is to replace the fundamental Gaussian mode with higher-order modes (HOMs) for the laser beam in combination with a specific coating design deposited on the mirrors. We will perform simulations to determine the most appropriate modes and then set up a tabletop experiment to apply these modes both in interferometers and squeezing sources.

The various sensors used in gravitation wave detectors require continuous development to keep up with the overall sensitivity increase. The phase camera developed at Nikhef provides information on the mode content of the laser beam to correct for the thermal aberrations introduced by the increased circulating optical power. We need to understand the data produced by the phase cameras to ease the control of the thermal aberrations. Currently, the phase camera provides only differential information about the phase of the beam. Our goal is to upgrade the hardware to allow absolute phase measurements.

The DR&D group leads the quadrant photodiode developments (QPD) for LISA, Virgo, and ET. Nikhef provides the quadrant photoreceivers for LISA, together with SRON and Dutch industry. These systems measure the tiny GW signals imprinted on the weak laser beams from the remote spacecraft and provide alignment of the optics via the segmented photodiodes. In Virgo, the current QPDs cause some unwanted scattered light and an upgrade of the sensors is needed to improve the overall sensitivity. The ET interferometer moves to silicon test masses and requires a longer laser wavelength to reduce optical absorption. Hence, new photodetectors that are sensitive at longer wavelengths will be developed by altering the Indium-Gallium ratio in InGaAs material and exploring new sensor materials like HgCdTe.



Testing new particle sensor concepts at Nikhef.

Blue-sky R&D: to strengthen the above research areas in the longer term, we need

→ Alternative (for industry non-standard) sensor doping profiles and geometry.
→ Integrate part of the electronics in the sensor layer to separate functionality.
→ Alternative sensor materials (e.g. SiC)
→ Alternative methods and structures for measuring with precise timing the passage of particles (similar to the 'Membrane' project).
→ Exploration of new detector technologies, such as "quantum sensors"

6.11 PHYSICS DATA PROCESSING (PDP)

MISSION

To shorten time-to-science-results by processing data faster, more effectively and more efficiently. Achieve this through R&D on algorithmic co-design with computing, storage, internetworking and federated collaboration architectures, and by constructing and operating the facilities that enable our physics programmes through the national and international computing infrastructure for science.

Goals

- Expand the reach of our applied advanced computing R&D in algorithms and (GPU) accelerators to the re-processing phase and more physics programmes, including new '4D' tracking options and ubiquitous machine learning. Pursue exploratory work on quantum computing, in collaboration with university computing sciences research groups, to investigate its potential.
- Drive technology R&D in networking and systems architectures for data-intensive processing, enabling early-design phase vendor engagement and stimulating valorisation of our results.
- Enable seamless collaboration for data-intensive experiments and the open science era.
- Operate a leading-edge e-Infrastructure, both for structured 'collaboration-wide' computing and as an analysis facility to shorten 'time-to-results' for Nikhef researchers. This infrastructure will constitute at the same time the validation environment for all three PDP action lines: applied advanced computing, advanced computing technologies and the infrastructure for collaboration.

Strategy

The Physics Data Processing (PDP) programme focuses its efforts on the specific elements of advanced computing most impactful for our physics programme and that align with the direction of the Dutch and European e-Infrastructures. In this broad landscape, Nikhef has selected the specialty topics with our existing expertise and physics programme needs will have the largest impact. We structurally embed this strategy in collaborations with the Dutch cooperative for education and research SURF, and the major European and physics-specific Infrastructures, including diverse organisations like GEANT, EGI.eu, the Worldwide LHC Computing Grid (WLCG), the International Gravitational Waves Network (IGWN), the ESFRI cluster with SKA and KM3NeT, and the European Open Science Cloud (EOSC).

The next order-of-magnitude increase in computing requirements, for the HL-HLC in terms of volume but also for the complexity challenge in gravitation wave analysis and for high-precision studies, makes it ever more urgent that our science algorithms exploit the capabilities of modern hardware to the utmost. Since it is obviously not a viable proposition to develop custom hardware for most use cases, the next generation of computing needs co-design of the algorithms and workflows with accelerated hardware (such as general-purpose GPU), networking (multi-terabyte, variable packet size), and parallel high-throughput storage systems. Larger and more diverse collaboration, such as between (astro)particle physics, computing science, machine learning and data science, and astronomy, put additional emphasis on the collaboration infrastructure: authentication, authorisation, group and role management structures, and the associated cybersecurity resilience, risk management in an inherently and intentionally open environment.

Applied advanced computing will focus on the algorithms for the novel '4D' tracking algorithms, and the accelerated systems that will enable novel algorithms to perform effectively and efficiently. Ubiquitous use of accelerated (GPU) computing is required also for the reconstruction and analysis phase, expanding from its use today in on-line event selection. Machine learning, both training and inference, will take centre stage and the PDP programme will pursue the new possibilities to expand its existing base in on-line acceleration also to the subsequent re-processing workflows. Energy consumption will be a driving factor in making computing feasible for our next generation experiments, and the co-design methodology, grounded in concrete measurements of power usage and processing efficiency, will be a core part of the PDP strategy in this area. At the same time, we will take care to ensure explainable results coming out of AI-generated outcomes.

Quantum computing (QC) offers the enticing possibility of accelerated algorithms for highly complex systems and in machine learning. While its potential results will likely bear fruit only in the latter half of the 2030s, it is essential to start already now to explore its potential. It has already become clear that 'porting' existing algorithms onto a QC system does not yield significant advantages: real benefits will require a re-thinking of the entire problem and algorithms used. In this strategy's timeframe, we will explore the possibilities offered by QC for applied advanced computing both for the LHC use cases as well as for gravitational waves research. However, a close collaboration with the university groups in computing sciences that are linked to the Nikhef partnership is a critically important element for these explorations.

The hardware and software infrastructure is an obvious critical element: it provides both the facilities to analyse physics results (and thus achieve that 'shorter time-to-science' objective that is at the core of the PDP mission), as well as constitutes the validation environment for both algorithm and collaboration-and-security research. Nikhef is uniquely placed to drive the development of advanced computing technologies: it is at the centre of European internetworking with its own data centre bringing together over 270 autonomous networks, it operates (together with SURF) the Dutch Tier-1 centre for WLCG, a large part of the computing for IGWN and our dark matter experiments (and for over 20 other science domains from health to structural biochemistry), and boasts a unique analysis facility designed for rapid turn-around computing on multi-petabyte datasets. We will continue to pursue our strategy to co-develop new hardware with vendors, based on an explicit best-of-breed vendor-neutral approach. By engaging in the early stages of systems development by suppliers, and strengthening our role as 'open innovation centre' (jointly with SURF), we act as an influencer for the direction where 'commodity-of-the-shelf' development is going in terms of intra-system data movement, data processing units, and networking. Leveraging our central internetworking position and the possibilities offered by dark-fibre links from Amsterdam to, e.g., Geneva, we will push R&D for 'packet-limited processing' (small packets, large bandwidth) that is needed for remote rare-event selection, networked remote storage, and research- or public-cloud bursting.

Data orchestration and compute data workflows across the global multi-domain infrastructure will change as data placement becomes more dynamic. This will result in changes in data and network traffic flows, and has the potential to improve effectiveness of the analysis facilities when these are considered in a coherent system with the structured re-processing facilities such as WLCG Tier-1s. It is the intention of the PDP programme to reinforce the group in this area, and thereby better exploit the applied algorithms and technologies areas.

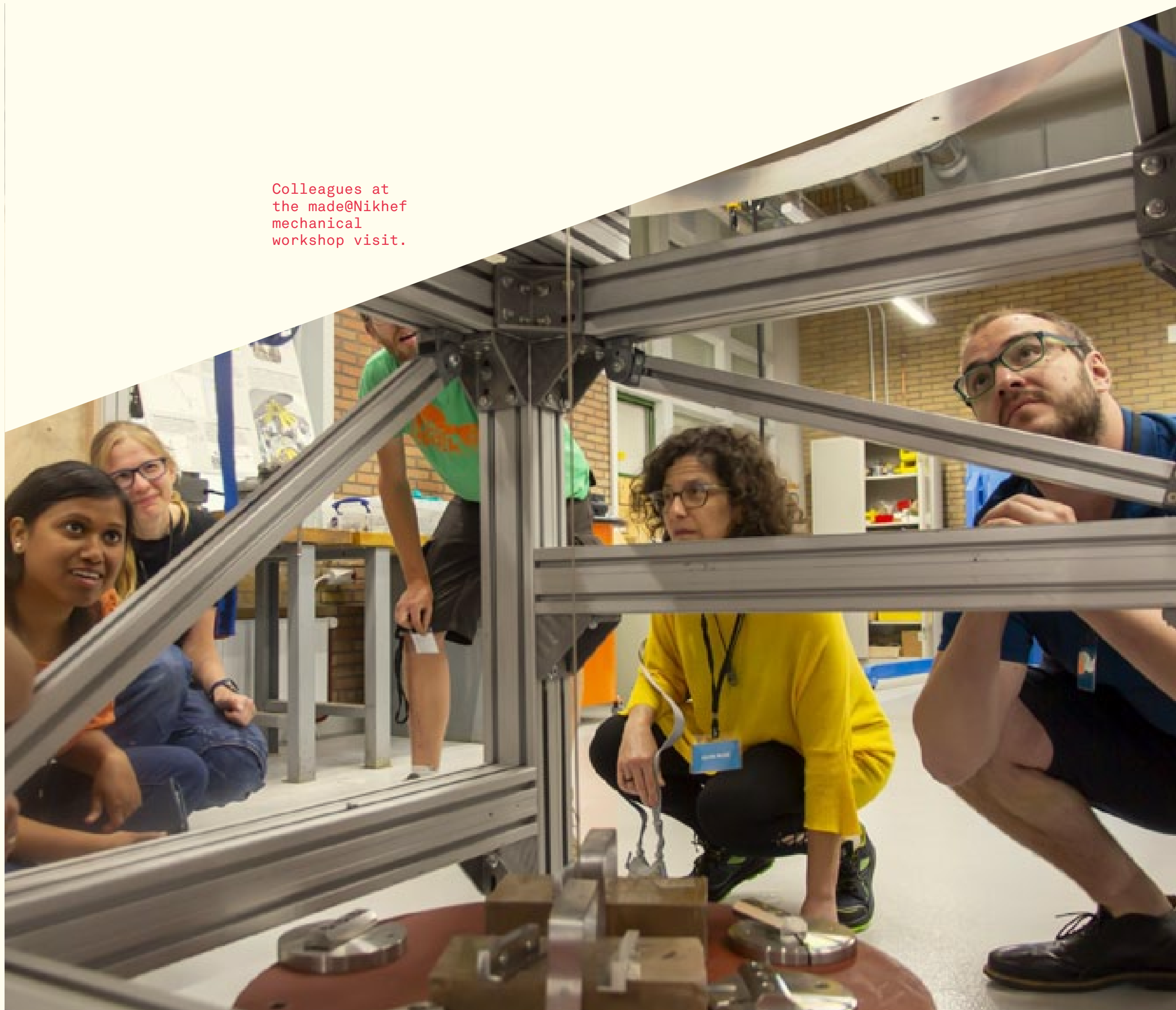
Testing new graphic processors for particle physics calculations.

The opportunities offered through large-scale open data, especially for multi-messenger astrophysics but for example also on the interface between physics data and machine learning, will drive the developments in ‘infrastructure for collaboration’. Authentication and authorisation infrastructure (AAI) interoperability, both between disciplinary data stores and in the EOSC, drives changes in technology and community structures. Nikhef’s ‘infrastructure for collaboration’ theme is exceptionally well placed to drive these developments and reap the fruits of our strong engagement with the EOSC and the research and e-Infrastructures that provide its substrate and services. OpenID Connect, federated research and educational AAI, and the traditional non-web access needed for large-scale physics analysis converge, and Nikhef will co-steer these development through participation in national (SURF, Thematic Digital Competence Centres), European (GEANT, EGI, and EOSC), and global (IGTF, REFEDS, eduGAIN, and WISE) groups. This will result in more ‘FAIR’ data that is scientifically sound, linked strongly to sustainable software, and with the infrastructure on which to ‘bring our data to life’.

The key element in achieving these objectives is the validation of algorithms, infrastructure design and the innovation results in real-world scenarios. In this sense, the other Nikhef programmes act both as ‘customers’ of the PDP computing results, but also as our experimental environment or ‘test bed’ for the R&D carried out as part of the PDP programme. This mutuality re-enforces the impact of the PDP programme – since it provides us with critical experimental data on the infrastructure – and at the same time fulfils a critically important function for the Nikhef physics programmes. They can leverage the large computing facilities that are operated jointly by the PDP programme and computing technology group, as well as benefit from the algorithm-R&D performed in collaboration with the PDP programme.

CROSS-GROUP MEETINGS AND ACTIVITIES

To strengthen cohesion between different groups, various events affecting different groups are currently organised. One such meeting is “Theory Meets Experiment”, where particle physicists from theory and experiment discuss common topics. Another is “Made@Nikhef” where technical departments showcase their work to a broader Nikhef audience. In addition, different groups often share PhD candidates, further strengthening ties between groups.



Colleagues at
the made@Nikhef
mechanical
workshop visit.

Questions and answers, Jamboree 2023, Amsterdam.

COLOPHON

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This strategy report forms, together with the self-evaluation report, input for the six-yearly evaluation of the institute. Both documents may be viewed online:
Digital version Strategy:
www.nikhef.nl/strategy2023-2028
Digital version Evaluation:
www.nikhef.nl/evaluation2017-2022

Organisation: