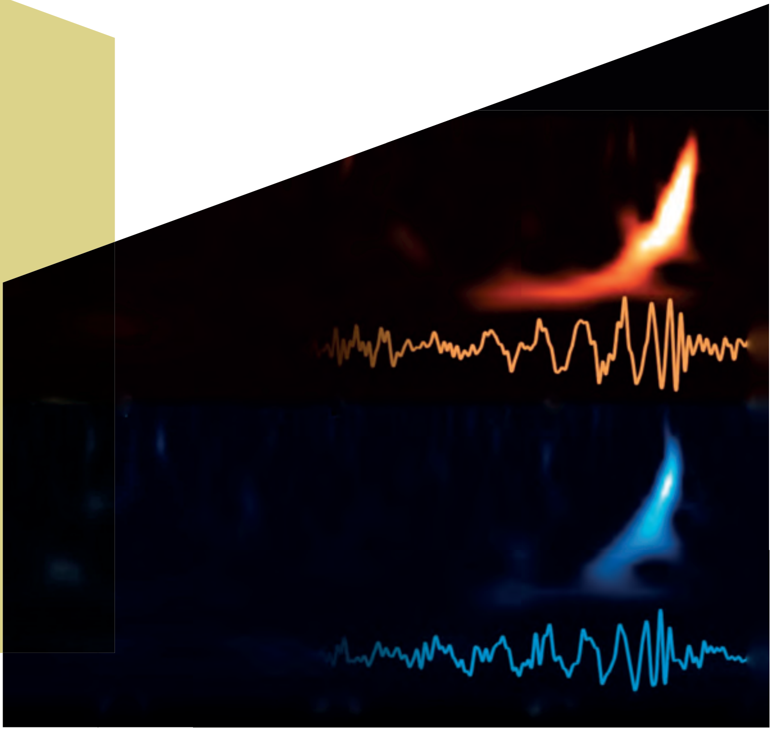
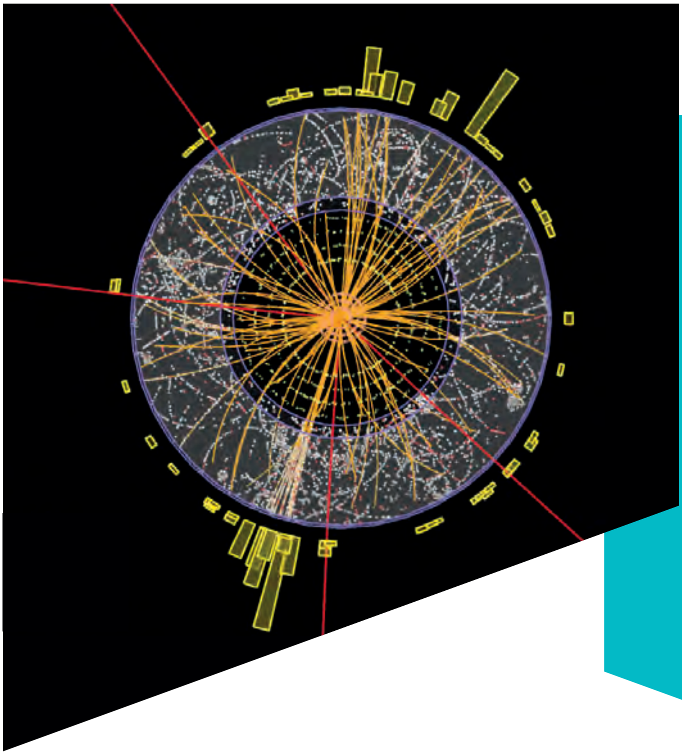
National
Institute for
Subatomic Physics

EVALUATION 2011 → 2016

Nikhef



First observation of
the chirp pattern of
gravitational waves
by the LIGO-Virgo
collaboration on
14 September 2015



Higgs candidate:
decay into four muons
as observed by the
ATLAS collaboration
on 14 September 2011

NIKHEF EVALUATION
2011 → 2016

NIKHEF MISSION

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

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

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

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

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01

INTRODUCTION

UNDERSTANDING THE UNIVERSE IN TERMS OF ITS ELEMENTARY PARTICLES AND FIELDS

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

In the last few years Nikhef has been part of historical events: the discovery of the Higgs boson, and the discovery of gravitational waves. The first, though long expected, was truly ground breaking: a nugget of vacuum, in the form of a fundamental spinless particle, is now known to exist. The second shows spacetime itself to be dynamical, and opens up a whole new research domain. Both discoveries are top scientific breakthroughs where Nikhef has played a major and visible role, with top ranked scientists and dedicated instrumentation. This report formulates the contributions of Nikhef in these and other endeavours.

Nikhef is the Dutch National Institute for Subatomic Physics. The research of Nikhef strengthens and extends the very successful tradition of particle physics of the last century. The development of particle physics is gigantic and besides its intrinsic fascination has proven to be extremely valuable in the technology and innovation of our society.

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

NIKHEF IN A NUTSHELL: A PARTNERSHIP OF NWO AND UNIVERSITIES

The Nikhef partnership has been established in 1975. The partnership consisted till 2016, of the FOM (now NWO-I) institute and the subatomic physics groups of four universities: University of Amsterdam, VU University Amsterdam, Radboud University and Utrecht University. On 19 February 2016 the University of Groningen joined the Nikhef partnership with the Van Swinderen Institute. Its low-energy eEDM experiment is now part of the Nikhef physics programme.

The core of the Nikhef partnership is worded in the first consideration of the Partnership Agreement: *"The importance of the research discipline of subatomic 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 key words. While at the start of the partnership more than 40 years ago, national activities in High Energy Physics and Nuclear Physics were brought together, forming the basis for the (Dutch) abbreviation 'Nikhef', Nikhef now comprises almost all activities in the Netherlands in experimental accelerator based particle physics and astroparticle physics; since 2000 Nikhef is no longer active in nuclear physics.

The strength of the partnership lies in its *integral approach* of participating in (international) experiments, in particular but not exclusively at CERN. As one of few European institutes Nikhef embodies this integral approach: from design, engineering and building very advanced instrumentation, using mechanics, electronics and computing expertise, to the analysis of data, where the involvement in the detector instrumentation renders a competitive advantage. This advantage is so evident for the university partners, that they accept to give up a significant part of their scientific *autonomy* to join the research choices made by the partnership.

The division of roles between the NWO-institute and university partners has evolved naturally over the years. More than half of the permanent scientific staff of the partnership is employed by the university partners. Usually a Nikhef programme is led by a university employed (full) professor.

Each university partner thereby ‘owns’ one or two Nikhef activities (programme lines), which provide them a clear profile in the partnership and in their own university.

Most of the technical and engineering support and facilities are concentrated in the NWO-institute. Temporary scientific staff (PhD students and postdocs) are also mostly employed by the NWO-institute. Appointing permanent scientific staff, whether at a university partner or at the institute, takes place using a selection committee in which the Nikhef director participates ‘ex officio’.

The integral scientific programme is led by the Nikhef director. Staff is consulted before any choices are made, but eventually the Nikhef director decides what will be included in the scientific programme. The Nikhef Board, in which NWO and the university partners are represented, formally approves this programme, including the budgets, taking the recommendations from Nikhef’s Scientific Advisory Committee into consideration.

Nikhef is very selective in its participation in experiments. Our participation is primarily guided by scientific goals, but we want to make a difference (‘focus and mass’). Our largest grant applications are therefore always submitted on behalf of the *Nikhef partnership*.

Due to this tight integration of NWO-institute and university partners, previous mission evaluations of Nikhef (in 2000, 2007, 2011) have always been from the perspective of the *Nikhef partnership*. In this very tradition, the partnership forms also the entity for the current self-evaluation and strategy.

Repeatedly this partnership model has been praised by external committees. RECFA, a body that regularly visits each country in Europe and provides recommendations on the status of its subatomic physics discipline, has expressed this again at its last visit to the Netherlands in 2012: *"The coordination of particle- and astroparticle physics through FOM-Nikhef and the associated universities is a role model for other countries."* In his response the then State Secretary for Education, Culture and Science, Halbe Zijlstra, acknowledged: *"I am glad to hear that this research community in a system that is highly governed by self-regulation, can achieve standards, that are internationally impressive and are even indicated as a role model for other countries."*

TABLE 01 **Involvement institute and universities in scientific programmes**

Shown are the number of physicists (PhD, postdoc, staff) working in 2016 on the programmes: *<3,** 3-6,***>6

	FOM	UU	RUG	VU	UvA	RU
ATLAS	•••				•••	•••
LHCb	•••		••	•••		
ALICE	•••	•••				
Neutrino Telescopes	•••				•••	
Cosmic Rays						•••
Gravitational Waves	••			•••		
Dark Matter	••	•			••	
Theoretical Physics	••	•	••	•	•••	••
Electric Dipole Moments	•••		•••			

COMPLIANCE WITH THE STANDARD EVALUATION PROTOCOL

This self-evaluation report conforms to the Standard Evaluation Protocol (SEP), used in the Netherlands to evaluate research entities. The unit of evaluation is the Nikhef partnership, as explained in the previous section.

The SEP uses three criteria along which the evaluation takes place: research quality, relevance to society and viability. Furthermore the assessment needs to comprise three more aspects: the PhD programme, research integrity and diversity. Below we provide an overview of which parts of this self-valuation document address the various issues:

TABLE 02 **SEP aspects**

Aspect	Addressed in
Research quality	Section Main results in the physics programme, Section Research programmes, Appendix
Relevance to society	Section Relevance to society, Appendix
Viability	Section Financial achievements in 2011 - 2016, Sections Personnel, Funding and expenses
PhD programme	Dedicated Section
Research integrity	Dedicated Section
Diversity	Dedicated Section

The NWO Board has added three evaluation questions to the SEP that also need to be addressed in the self-assessment.

TABLE 03 **NWO questions**

Question	Addressed mainly in
What is the institute's added value in the national context and its international position?	Section Nikhef in a nutshell: a partnership of NWO and universities, Appendix: Research programme, per programme: Nikhef contributions.
How does the institute stimulate and facilitate knowledge utilization and open access?	Section Relevance to society, Section Research Integrity/Open data
How does the institute's structure, size and financial policy contribute to its mission?	Sections Organisation, Personnel, Funding and expenses

Finally, the SEP encourages the research unit to list *Key output indicators*. In the table below we present a number of output indicators, pertaining to the period 2011 - 2016, with the links to where they are shown or discussed in more detail.

TABLE 04 **Output indicators (2011-2016)**

Assessment Dimensions	Quality Domains: Research quality	Quality Domains: Relevance to society
Demonstrable Products	Research products for peers: • Research articles: 2402 • Theses:130 • Instruments; see individual Research Programmes • Software: FORM project, see Table 7	Research products for societal target groups: • Outreach lectures: 483, see section Relevance to society
Demonstrable use of products	Use of research products by peers: • Citations: 143,440 • Bachelor, Master students, see section Education	Use of research products by societal groups: • Patents/licences: 7, see overview in Appendix • Grid Computing (Big Grid): see Table 5 and Table 7 • Nikhef datacenter: 130 clients, see section Knowledge and technology transfer • Use of Clean Room facilities e.g. by PANalytical, see Table 19 • Industrial research collaborations and contract research agreements: see Table 19 • Organization Route 5 of the Dutch National Research Agenda (NWA), see section External Developments • School children programmes, see section Education
Demonstrable marks of recognition	Marks of recognition from peers: • Science prizes: see individual Research Programmes • FOM Valorisation Prize: vd Brand • Personal Grants: Rubicon 2, Veni 4, Vidi 6, Vici 4, ERC 5 • Invited lectures: 1375 • President CERN council: S. de Jong • Membership of 125 external scientific boards, see overview in Appendix • Organization of 47 workshops and conferences, see overview in Appendix • Grants, see overview in Appendix	Marks of recognition by societal groups: • Public prizes: Snellius medal 2015 for ATLAS group, Physica prize 2013: F. Linde and S. Bentvelsen, see Narrative - Higgs • Valorisation funding: a.o. 1,5 M€ by Shell, see Table 19 • Start-up funding, see Table 19 • KNAW Memberships: H. Falcke, F. Linde, R. Loll • Royal Dutch Society of Sciences: S. Bentvelsen • Academia Europaea memberships: H. Falcke, R. Snellings, S. de Jong, A. Mischke and R. Loll

02

LOOKING BACK: SUMMARY OF RESULTS IN 2011→2016

In Nikhef's Strategic Plan 2011 -2016 we have formulated several ambitions, to be enabled by a financial scenario. In this chapter we summarize the results of the previous period, including the recommendations provided by the evaluation committee of 2011. Without any doubt, the discovery of the Higgs boson (2012) and the first detection of gravitational waves (2016) are the scientific highlights of this period!

The organizational highlight has been the admittance per 2016 of the Van Swinderen Institute of the University of Groningen to the Nikhef partnership. Funding highlights are the LHC physics programme (16,8 M€) acquired in 2013 and the LHC detector upgrade investments (15,2 M€) acquired in 2014.

MAIN RESULTS IN THE PHYSICS PROGRAMME

TABLE 05 **Results in the scientific programmes**

Programme	Mission 2011	Main result
ATLAS	To find and study the Higgs particle(s) responsible for the generation of mass. To search for physics beyond the Standard Model, such as supersymmetry, large extra space-time dimensions, or unexpected phenomena.	Discovery of the Higgs boson.
LHCb	To search for particles and interactions that affect the observed matter-antimatter asymmetry in the nature, by making precision measurements of B-meson decays.	Observation of rare B-meson decays and time varying CP violation.
ALICE	To study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected.	Observation of a near perfect liquid of the quark-gluon plasma.

CONTINUE →

Programme	Mission 2011	Main result
ANTARES/ KM3NeT	To discover neutrino sources in the nature. The observation of cosmic neutrinos will provide information about the origin of cosmic rays, the mechanism of particle acceleration and transient astrophysical phenomena.	Deployment of first KM3NeT strings.
VIRGO, LISA & ET	To detect gravitational waves, or ripples in the fabric of space-time, that are produced by violent events throughout the nature.	Detection of gravitational waves in the LIGO-VIRGO collaboration.
Pierre Auger Observatory	To study the origin and composition of ultra-high-energy cosmic rays (UHECRs), their interpretation and consequences for the understanding of astrophysical objects, and the interaction of these ultra-high-energy particles with the Earth's atmosphere.	Mass composition studies in ultra-high-energy cosmic rays. First deployment of radio detection of CR.
XENON	To identify and study the particles responsible for dark matter in the nature.	Construction and start of the scientific exploitation of XENON1T.
Theory	To describe and explain the properties and interactions of subatomic particles. To study theoretical models, such as the Standard Model, for predicting and describing new and existing experimental or observational results, mostly in the framework of quantum field theory. To develop analytical and computational tools for these studies.	World class results in perturbative field theory, B-physics, cosmology, gravity.
Detector R&D	To develop state-of-the-art detector technologies to advance future particle and astroparticle experiments. To take a leading role in implementing these technologies in next generation experiments via (inter)national partnership. Collaborations with industrial partners are actively pursued.	ERC MEMbrane project reached Secondary Electron Yield of more than 4 in new photomultiplier device ('Tynode').
Physics Data Processing	Operation of state-of-the-art computing resources for Nikhef physicists, participation in national and international distributed computing infrastructures, and R&D on large scale scientific computing.	From the successful BiG Grid project to the establishment of a coordinated national e-Infrastructure led by the SURF foundation.

FINANCIAL ACHIEVEMENTS IN 2011 - 2016

In our financial scenario of 2011 and beyond we have listed our plans and expectations with regard to funding our scientific and general ambitions, building on top of the funding that at that time was 'secured'. The table below shows the results.

TABLE 06 **Plans and achievements**

Activity	Aim	Result
LHC physics	Acquire an 18 M€ FOM-programme to continue the exploitation of the LHC experiments (with PhD positions and postdocs) after 2013 - 2015.	In 2013 a 16,9 M€ grant has been obtained covering PhD positions, postdocs, M&O contribution and travel costs for the period 2014 - 2021.
LHC Physics and Tier-1	Acquire investment funds for the LHC detectors upgrade and continuation of the WLCG Tier-1 (16 M€).	In 2014 a 15,24 M€ grant has been obtained from the Dutch National Roadmap fund.
Direct dark matter searches	Acquire ~1,5 M€ FOM programme funding for PhD positions and postdocs.	In 2012 a 2 M€ grant has been obtained, including 0,6 M€ for the theoretical activities, led by the UvA.
ANTARES/ KM3NeT	Acquire FOM programme funding.	Not submitted due to other priorities. Small funds (2 PhD positions and postdoc) made available by director from mission budget.
Pierre Auger Observatory	Acquire FOM programme funding.	Not submitted due to other priorities. One PhD position made available from director's budget.
Pierre Auger Observatory	Acquire investment funding for upgrade (~2 M€).	Not submitted due to other priorities. Instead 450 k€ investment budget allocated from mission budget.
VIRGO	Acquire FOM programme funding of around 2 M€.	Initial proposal turned down. Special request by Nikhef director, supported by University partners VU and RU has resulted in a 1 M€ FOM programme grant (2015 - 2020).
VIRGO	Acquire investment funding for Advanced Virgo of around 2 M€.	NWO-Groot investment proposal granted for 2 M€.

CONTINUE →

Activity	Aim	Result
Theoretical Physics	Acquire FOM programme funding.	Two programme proposals have been granted, one coordinated by Nikhef.
Industrial Partnership Programme	Acquire IPP of around 0,9 M€.	No IPP proposals submitted. Instead: research collaboration agreement with Shell concluded, totalling 1,5 M€. Various other industrial collaborations initiated.
Mission budget	Increase with 1 M€ annually.	Not rewarded by FOM nor NWO Board.
Project funding	Acquire at least 2 M€ annually from (mainly) NWO and EU funding.	An annual average of 2,4 M€ FOM and NWO project funding acquired. In addition 2,3 M€ annual average of project funding acquired from other sources (a.o. EU, industrial).
Other income	Obtain net income from lease and housing activities of at least 0,9 M€.	Average net income: 1,8 M€ annually.

In summary most of our financial goals have been realized, with as highlights the very large grants for the LHC experiments: both for the scientific exploitation and for the detector upgrades and computing. This certainly is an illustration of Nikhef's viability. We are particularly happy, that we have been able to succeed in acquiring much more than the already ambitious level of other project funding stated in our current strategy (a table with all funding acquired in the period 2011- 2016 can be found in the appendix).

Due to limitations in the FOM programme funding opportunities we had to prioritize programme proposals. In some areas we have reverted to tapping into the mission budget to prevent some activities (Pierre Auger, ANTARES/KM3NeT) going below a critical level in terms of scientific exploitation (PhD students, postdocs). In the area of investments we have prioritized a proposal for the XENON Dark Matter experiment, which however was not granted. In the last year of FOM programme funding (2016) we have chosen to opt for submission of the programme proposal from our newest University partner (Groningen) on the electron Electric Dipole Moment (eEDM), which fortunately has been granted for more than 2 M€.

FOLLOW UP OF RECOMMENDATIONS OF THE 2011 REVIEW PANEL

The previous NWO evaluation panel visited Nikhef in 2011 to provide feedback over the period 2007-2010. The NWO panel formulated recommendations on general issues, LHC experiment activities, Astroparticle Physics experiments, Theory, Detector R&D and Scientific computing. We list only those recommendations in the table below, which have not yet been addressed above.

TABLE 07 **Follow up of recommendations from the 2011 evaluation panel**

Activity	Recommendation	Follow up
KM3NeT	The panel expects Nikhef to continue its optimization of the KM3NeT detection technology and urges Nikhef to strive towards siting the KM3NeT headquarters in the Netherlands.	The KM3NeT optimization has been completed and the first full detector units have been deployed. KM3NeT 2.0 has been placed on the ESFRI Roadmap 2016. The Netherlands will take the initiative to organize KM3NeT as an ERIC headquartered in the Netherlands. EU funding (for a preparatory phase project) has been acquired.
Pierre Auger Observatory	The panel endorses the further development of the radio detection technology for cosmic rays.	An international consortium with strong Dutch participation and under Dutch leadership has developed this technology to a state that is now fully understood (simulation-wise and in field-operation-wise).
VIRGO	The panel endorses Nikhef's Advanced Virgo participation and, at a later stage, ET. The panel recommends that Nikhef applies for full EGO membership. The panel endorses furthermore Nikhef's funding request within the NWO-Groot scheme for Advanced Virgo.	NWO-Groot funding for Advanced Virgo has been acquired. Nikhef has not yet entered into full EGO membership. We rather concentrate on transforming EGO into a broad European gravitational-wave organisation, also governing future ground-based gravitational-wave observatories, in particular the Einstein Telescope (ET) project. A possible location for ET is in the Netherlands. Nikhef has initiated a working group investigating this possibility and later preparing a bid.

CONTINUE →

Activity	Recommendation	Follow up
Theory	The panel observes that the FORM project is unique to Nikhef and that its long term support is vital.	FORM inventor Jos Vermaseren received in 2012 an ERC Advanced Grant. In parallel Nikhef entered discussions with notably Zürich University (CH) and the Institute for Particle Physics Phenomenology in Durham (UK), to see if we can jointly fund a FORM position ('fellowship') rotating between our institutes.
Theory	The panel recommends to continue efforts in gathering external funding.	Theory has been one of the most successful activities with respect to external funding, with e.g. three ERC Advanced Grant holders and several Marie Curie Initial Training Networks.
Theory	The panel recommends to (further) focus on theoretical work directly linked to Nikhef's experimental activities.	Nikhef has hired theory staff, that interacts very closely with Nikhef experimenters even leading to joint publications (e.g. Robert Fleischer with the LHCb experiment). Vice versa Nikhef experimenters team-up with theorists at Nikhef and with theorists not formally belonging to the Nikhef consortium alike. The latter notably regarding the XENON Dark Matter experiment (Gianfranco Bertone from the UvA).
Detector R&D	The panel recommends that, given the increased demand for valorisation, the detector R&D group develops a strategic plan dealing with balancing core Nikhef activities (curiosity driven research) with valorisation activities, IP and spin-offs.	Several detector R&D topics have been identified, which are both attractive from the perspective of instrumentation for Nikhef 's primary research and for application in industry. These topics include ASICS development, MEMS based accelerometers (e.g. for gravitational waves detection and oil and gas exploration), MEMS based photomultipliers and hadron therapy detection techniques. Based on these insights a strategic plan for detector R&D has been developed.
Scientific Computing	The panel recommends with NL/Tier1 established that Nikhef reflects upon its long-term ambitions in the field of scientific computing.	The Physics Data Processing (PDP) group within Nikhef has produced a strategy document. Key elements in this strategy are: 1) scaling R&D, concerning computing problems arising from increasing the scale of the infrastructure; and 2) scalable multi-domain security, around aspects of identity management, access control and provisioning and cross domain operational security and incident response. In these two areas Nikhef has built up considerable expertise, recognized at the national and the European (international) level.

Activity	Recommendation	Follow up
Scientific Computing	The panel expects the Netherlands to maintain its role as a major partner in the WLCG.	The NL/Tier1, built up through the 'BiG Grid project' (2007–2012), has been adopted by the national e-infrastructure as operated by SURF and its subsidiaries. Nikhef's role in the national e-infrastructure has been continued, underpinned by an agreement with SURFsara (2013 - 2018). Investments in the NL/Tier1 has been included in the (granted) funding request for the LHC detector upgrades.
General	Both the evaluation panel and NWO-AB urge Nikhef to improve the gender balance.	In 2004 the Nikhef consortium had only two female staff members with a PhD degree while today the consortium has eight female staff members with a PhD degree, two of which are (full) professor. Recently Nikhef has offered staff positions to two female candidates, following a dedicated selection procedure ('WISE') for female staff.
General	Both the evaluation panel and NWO-AB urge Nikhef to reduce the duration of the PhD research project.	The median PhD duration has decreased every year since the evaluation from 5.3 years in 2011 to 4.5 years in 2015/2016 (defined as the time elapsed between the start of the PhD contract date and the PhD graduation date).
General	The panel recommends on many occasions (VIRGO, Auger, XENON, detector R&D and grid computing) hiring of additional staff..	Due to funding limitations this has only been marginally possible. Instead Nikhef has put effort in expanding its role as national coordinator by enlarging the Nikhef partnership. Most notable result is the admittance per 2016 of the VSI group at University of Groningen (LHCb, Theory and eEDM). Very recently (2017) Nikhef has decided to open staff positions on detector R&D and physics data processing.

HIGGS: FROM INTERNATIONAL EXPERIMENT TO NATIONAL KNOWLEDGE

By Dorine Schenk

The discovery of the Higgs boson resulted in euphoric particle physicists and a Noble prize. But what did this fundamental research do for society? And why are even barbers excited about the discovery?

"As a layman I would now say I think we have it." With these words, CERN Director-General Rolf-Dieter Heuer, announced on July 4th 2012 that a particle with the characteristics of the Higgs boson was found in the ATLAS and CMS detectors at the LHC. This discovery will enter the books as one of the biggest scientific breakthroughs.

A large group of Nikhef researchers, working for the ATLAS experiment, played an important role in this major scientific discovery.

Parts of the ATLAS detector, for example the equipment for the muon spectrometer, were designed, built and tested in Amsterdam, since Nikhef has a lot of in-house knowledge and expertise on developing particle detectors and detection software. Nikhef's knowledge about detection technology also resulted in the spin-off Amsterdam Scientific Instruments (ASI), which produces technology for a diverse range of industries, from agriculture to dental industry. However, for some detector components the knowledge and skills of outside companies were required. The Endcap Toroid, for example, was built by the Dutch companies Schelde Exotech and Brush HMA.

Nikhef researchers also contributed to the ATLAS experiment by designing software to screen the enormous amount of data coming from the detector to look for the Higgs boson. The collisions between protons which take place inside the experiment produce about 1 GB of data per second. It takes a tremendous amount of data management and cleverly programmed software to find the decay products which point to a Higgs boson. These contributions to one of the most important fundamental discoveries of this century did not go unnoticed. Nikhef researchers Stan Bentvelsen and Frank Linde received the *Physicaprijs* 2013 for their contribution to the Higgs discovery. And the *Snellius medal* 2015 was awarded to the Dutch ATLAS group for the same reason.

The search for the Higgs boson was an enormous quest, requiring high-tech detectors and clever software. The stakes were high; the boson was the last missing piece of the puzzle called the *Standard Model* of particle physics. This theory describes the elementary particles and their interactions. All the predicted particles had been seen in experiments, except for the Higgs boson, which was needed to explain why the other particles have mass.

All over the news

The scientific community was overjoyed when this last puzzle piece fell into place. This excitement was soon shared with the general public. "It answers one of the biggest questions we had", Ivo van Vulpen researcher at Nikhef and member of the ATLAS experiment, enthusiastically told one of the main Dutch national news channels, the NOS news, on the day the discovery was announced.

More Nikhef scientists shared their joy with numerous national news programmes and

newspapers. “The search for the Higgs boson is research driven by curiosity”, Nikhef researcher and ATLAS member Paul de Jong told the Volkskrant. Almost all national papers wrote about the quest for the missing particle and the researchers who discovered it. Nowadays almost everyone has heard of the Higgs particle. “Even my barber was excited about it”, Nikhef professor Wouter Verkerke says.

It is clear from the significant public interest in the discovery that it fulfils the intrinsic desire of mankind to explore and acquire knowledge. To meet the demand from the public to learn more about the Higgs boson, Nikhef researchers engaged in numerous outreach talks.
Furthermore, to show everyone the road travelled by many scientists to get to this discovery the hour-long ‘Higgs, into the heart of imagination’ was shown on national television on the evening of the announcement. This documentary, made by the Dutch film makers Hannie van den Bergh and Jan van den Berg, follows Stan Bentvelsen, who led the Dutch ATLAS team, and other scientists during the preparations for the start of the ATLAS experiment. Meanwhile, physicists explain what the Higgs particle is and why it is so important for our understanding of the world around us.

The fact that people are interested in this fundamental research and want to learn more about the consequences is clearly shown in the *Nationale Wetenschapsagenda*. This initiative let everyone send in the science questions they want Dutch researchers to investigate. These questions were categorized in 25 ‘routes’. The dozens of questions about the Higgs research can be found in route 5, called ‘Building blocks of matter and fundaments of space and time’. This route has great overlap with the research done at Nikhef and is organised by Stan Bentvelsen.

Higgs and kids

The particle physics research done at the LHC is also a great way for Dutch high-school students to learn about science and technology. Nikhef offers annual one-day masterclasses where they learn how collisions of protons in the LHC result in the creation of new particles. They even get to analyse real data from the LHC. Paul de Haas, a high-school physics teacher from Kandinsky College in Nijmegen visited CERN as part of the High School Teachers Programme. The visit inspired him to set up a project about particle physics for high-school students. He even returned to CERN with nine senior high-school students. This way the students could experience the life of scientists. “I think the most impressive thing was that all of the people here are just people like us,” said Inge Verheul, one of the students. “And when I look here at CERN there are a lot of girls.”

Big, bigger, biggest data

Getting secondary school students interested in particle physics is not only important for the scientific community. The skills acquired during physics education and working in particle physics are in high demand in the labour market. Working with advanced detectors and designing software are abilities favoured by the high-tech and IT industry.

“At the ATLAS experiment I learned to extract interesting information from enormous amounts of data coming in with high speed”, tells Sander Klous, former member in the ATLAS group and now partner in charge of Data & Analytics at KPMG Advisory in the Netherlands and member of the global Data & Analytics leadership team of KPMG. “There are 3500 people working on the ATLAS experiment; it’s basically a factory. You learn to do science in an industrial way.” The skills people learn when working for such a high level research facility are useful in businesses like KPMG. “About 75% of my team has worked at Nikhef.”

KPMG is not the only company that values the skills people acquire working for the ATLAS experiment. More and more businesses are working with *big data* and need people qualified to analyse these high data streams. Compared to the data produced at the LHC most *big data* is child’s play. Klous: “I tell my customers: if you think you’re working with big data, I have a story about real big data.”

The discovery of the Higgs boson is just the beginning of the story. Every year new students and researchers join the LHC experiment to solve the mysteries of this particle and other building blocks of the universe. “We think there are many more tiny particles waiting to be discovered”, as Van Vulpen tells us in a TV-program for children, Klokhuis. We still do not understand why the Higgs particle has the characteristics that were measured at the LHC. And the answer to that question might open a whole new world of particle physics. “We just saw the land we know disappearing at the horizon”, says Bentvelsen. “Now we are sailing on the open sea, looking for new, unknown places, waiting to be discovered.”

03

ORGANISATION, PERSONNEL, FUNDING, OUTPUT, RELEVANCE TO SOCIETY

ORGANISATION

The Nikhef organizational structure as sketched in this section encompasses the Nikhef *partnership*, and therefore includes the NWO-institute and the university groups.

Governance: boards and bodies

This evaluation concerns the period 2011-2016 in which the 'FOM' governance structure has been in place. In this 'FOM-period' the Executive Board of FOM was the main decision-making body of the foundation and thereby responsible for governing the affairs of the institute. Meetings between the institute director and the Executive Board were scheduled when necessary, e.g. for discussions on strategic issues.

The Nikhef partnership (NWO-institute plus university partners) is governed by the Nikhef Board. This consists of seven members: two members assigned by NWO-I, and one by the governing boards of each of the five university partners. This Board approves the joint scientific programme of Nikhef and the annual budgets, as provided by each partner. The Nikhef Board meets once a year.

Until 2017 the Nikhef director has been appointed by FOM for a 5-year term with the option of a second 5-year term. The appointment always needs the approval of the Nikhef Board. During the period covered by this review prof. dr. Frank Linde has served as director until 1 December 2014, followed by prof. dr. Stan Bentvelsen, appointed for an initial period of 5 years.

The 'Scientific Advisory Committee' (SAC), consisting of (maximum) seven international experts in Nikhef's fields of research, is the external advisory body for the Nikhef Board. The SAC meets once a year. Members are appointed by the Nikhef board on a proposal by the Nikhef director .

Group structure

The research activities are organised as 'programmes'. Each programme has a programme leader (PL), appointed by the director, who is responsible for all activities and personnel in his/her research line, including the share contributed by the university groups. Currently there are 11 programmes. Three of these are LHC experiments (ATLAS, LHCb, ALICE) and four are astroparticle physics experiments: neutrino telescopes (ANTARES/KM3NeT), gravitational waves (VIRGO/LIGO, ET), cosmic rays (Pierre Auger Observatory) and direct Dark Matter searches (XENON1T). Since 2016 a low-energy precision research activity has been added (eEDM: measuring the electron electric dipole moment). The remaining research base activities are: Theoretical Physics, Detector R&D and Physics Data Processing.

The technical expertise is organized in three groups, each led by a technical group leader (TGL): computing technology (CT), electronics technology (ET) and mechanical technology (MT). These groups do not include the technical manpower at the university groups, which have a local embedding. The support section ('Beheersectie', BS) led by the institute manager, consists of the departments for financial administration, facilities and datacenter, occupational health and safety, secretariat & reception, library and staff including project management support. Two other staff departments, personnel affairs and science communication, report directly to the director.[1]

Internal management, bodies and meetings

Daily management of the institute takes place in the Directorate Team (DT), consisting of the director, institute manager (who also serves as deputy director) and head of the personnel department; the DT is supported by the head of the secretariat. During 2015 and 2016 the DT was extended with a fourth member, prof. dr. ir. Els Koffeman, as manager scientific instrumentation.

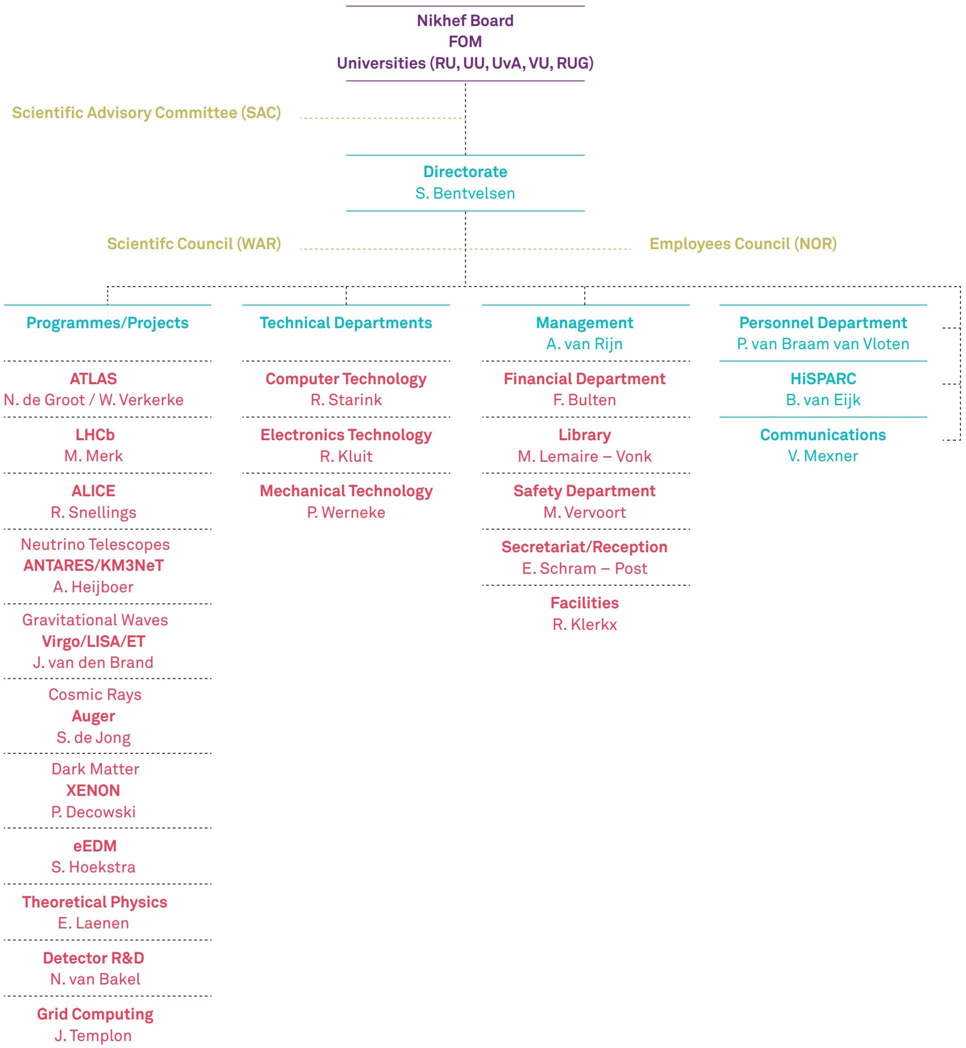
The institute works council ('Nikhef Ondernemingsraad'– NOR), a body required by Dutch law for organizations with 50 or more employees, represents Nikhef personnel and holds meetings with the director on average every two months to discuss developments within the institute. The NOR consists of Nikhef employees who are elected by all Nikhef personnel in bi-annual elections. The NOR is consulted by the director in cases prescribed by law, in particular on safety and working conditions.

Scientific policy is discussed in the scientific council ('Wetenschappelijke Advies Raad'– WAR), which serves as the internal advisory body for the Nikhef director. The WAR meets four times a year.

[1] Current SAC members are: T. Nakada, N. Glover, Ch. Spiering, H. Abramovich, J. Mnich, B. Erazmus

For the staff meeting ('Stafoverleg'), held with the same frequency as the WAR and directly preceding it, all permanent scientific staff and the TGLs are invited to attend. The annual scientific meeting of Nikhef (jamboree) is held in December and forms the stage for each group to present the scientific highlights of the year.

FIGURE 01 **Nikhef 2016 Organigram**



Project structure for scientific instrumentation

For more than two decades Nikhef has been using a so-called 'project matrix' structure for carrying out large scientific instrumentation projects. Such a project, which is usually part of a larger programme, is assigned to a project leader, who composes a project plan that contains –apart from technical and financial requirements– the estimated manpower requirements and a planning with milestones, which are refined in discussions with the technical group leaders. If agreed the manpower is assigned by the director. The overall manpower planning is updated twice a year. Progress on projects is reported in the Project Plans Meeting ('Overleg Project Plannen'– OPP), which is held every two months. Manpower priorities between projects within a programme are decided by the programme leader; priorities between different programmes are decided by the director.

The project matrix structure has worked quite well, although permanent attention is needed to deal with the inherent tension between the hierarchical line (technical group leaders) and the project line (project leaders). This requires clear rules, effective communication and adequate leadership. Recently all key players (technical group leaders, project leaders, programme leaders and the directorate) have been updated on the rules of engagement for project management. In addition, all junior project leaders have followed a four day project management course to learn leading a project in a project-matrix structure.

PERSONNEL

People make Nikhef what it is today. The institute's viability is mainly secured by a healthy, competent and diverse population of scientists, technicians and support staff. Nikhef puts much effort into hiring, enabling and developing its staff in order to continue its permanent pursuit of scientific excellence, societal relevance and knowledge transfer.

In this section, the quantitative and qualitative composition of Nikhef staff is described. Also, we will elaborate on the actions that are being taken to ensure optimal competence and diversity of Nikhef staff.

QUANTITATIVE EVALUATION

The number of personnel, expressed in full–time equivalents (fte) at Nikhef has increased in the period 2011–2016 from about 281 to 296 fte (Table 8). The number of permanent scientific staff is now at a level of about 71 fte, an increase with more than 10 fte. This is mainly due to the admittance in 2016 of University of Groningen to the Nikhef partnership. The number of postdocs is rather volatile, mostly because it depends on the availability of funding (grants). Nikhef typically hosts around 30 postdocs. The number of PhD students increased significantly (from 81 to 100), due to a combination of increased success in obtaining research grants and university groups joining Nikhef.

The number of engineers and technicians has decreased from 84 to around 70 fte. In 2011, Nikhef was still in the aftermath of the delivery of immense technical efforts for the LHC experiments. The finalization hereof made it possible to decrease the number of technical staff. This decrease has been established through 'natural attrition'. At the moment, Nikhef is in the process of consolidating the capacity of technical staff members, and at the same time creating more flexibility in the staff population. This flexibility is partly created by establishing a flexible shell of personnel members with fixed term contracts and temporary workers. The aim is to reach a balance at 70% of technical and support staff having a permanent contract. A more flexible personnel population allows for more flexibility in acquiring (new) technical expertise, also in other forms than offering a labour contract (such as outsourcing, insourcing, secondment, etc.). Furthermore, this policy enables Nikhef to absorb income fluctuations without having to fall back to compulsory redundancies.

TABLE 08 **Development of staff 2011-2016 per category**

Nikhef staff	**2011**		**2016**	
	#	FTE	#	FTE
Scientific staff	64	60,6	73	71,3
Postdocs	27	26,8	29	28,8
PhD students	82	81,1	102	100,4
Total research staff	173	168,5	204	200,5
Technical staff	84	83,8	72	69,8
Support staff	32	29,3	29	25,4
Total staff	**289**	**281,6**	**305**	**295,7**

Most Nikhef staff members are employed by NWO-I (the former FOM foundation). However, from Nikhef's *permanent scientific* staff 55% is employed by the university partners. This includes 22 full professors (2016). Thirteen scientific staff members employed by NWO-I hold professorships at a partner university or at one of the other universities in the Netherlands. In total, almost half of the scientific staff (35 out of 74 in 2016) holds a professorship. Around 80% of PhD students are employed by NWO-I, the others are employed by the universities. Postdocs are also mainly employed by NWO-I. The vast majority (more than 95%) of the technical, engineering and support personnel is employed by NWO-I.

DIVERSITY

Apart from skills and competencies, employees bring among them personal characteristics, partly consisting of their cultural background and gender. Since these two characteristics are very important for a balanced employee population, there is much emphasis on diversification.

Nikhef's working environment is of a great diversity, with literally all nationalities, religions and cultures represented, both male and female. And even a further increase of the diversity is likely in the future. As a result, the viability of Nikhef is depending on its ability to act in such a diversified context.

Nikhef's most powerful tool to create a balanced staff population is recruitment. Mainly through recruiting new staff from diverse backgrounds and of both sexes our staff population will optimally blend in with our international peers, and thus will ensure the institutes viability for years to come. Diversification efforts aim at three areas: gender diversity, cultural diversity and age diversity. We'll further elaborate on these efforts in the following paragraphs.

Gender diversity

Nikhef fosters its name as a reputable institute and over the years it has gained a good name among ambitious fellow physicists. As a result, the sourcing of scientific staff is a smooth process. Vacancies for full professors as well as postdocs and PhD students are filled in with relative ease. This offers Nikhef the opportunity to be selective with new employees and makes it possible to apply preferential policies when hiring new staff members.

Unfortunately, this counts less for technical staff members, who are usually more difficult to find, partly because the institute is less well known among the general public. For this reason, improvements have been made in the recruitment processes and support over the past years.

In order to decrease gender biases in selection committees, trainings and workshops have been attended by many recruiting Nikhef staff members. In 2014, FOM organized a Gender Awareness workshop that has been attended by several Nikhef staff members. Recently, Nikhef has actively taken part in the workshops organized by the GENERA project, and has opened a vacancy for a WISE fellow.

TABLE 09 **Personnel of Nikhef, in 2011 and 2016**

	2011				2016				development 2011-2016	
	total	M	V	% female	total	M	V	% female	Δ	relative change
Scientific staff	60,6	57	3,6	6%	71,3	62,1	9,2	13%	7%	117%
Postdocs	26,8	23	3,8	14%	28,8	20	8,8	31%	16%	115%
PhD students	81,1	65,3	15,8	19%	100,4	75,4	25	25%	5%	28%
Technical staff	83,7	79,1	4,6	5%	69,9	66,6	3,3	5%	-1%	-14%
Support staff	29,3	21,5	7,8	27%	25,4	17,5	7,9	31%	4%	17%

The result of all efforts made can be found in Table 9. Although significant improvements have been achieved, the conclusion must be drawn that there still is imbalance to be dealt with. Nikhef typically opens one or two vacancies for scientific staff members every year. The speed with which the imbalance can be repaired obviously is limited.

The number of females in technical and support staff did not increase significantly in the review period. It appears to be hard to find skilled female technicians. The issue is recognized, and action will be taken to create a more balanced population of technicians. One concrete action is that more female interns are selected in the technical departments.

With typically one or two vacancies per year for Scientific staff members it is difficult to set hard targets for gender equality. Nonetheless, for permanent positions, Nikhef has chosen to commit itself to hire at least one female scientist every second job opening. Over the past five years, Nikhef more than realized this ambition. In order to maintain this positive development, the target will remain in place. Moreover, Nikhef aims at embracing all initiatives that stimulate the hiring of female scientists.

Cultural Diversity

Nikhef is a culturally diverse organization. The institute participates in multinational research projects. Learning to collaborate within these projects is a necessity to be successful in this context. Moreover, Nikhef hosts employees from all continents. In 2011, the institute hosted 25 nationalities, in 2016 this increased slightly to 26 nationalities. Table 10 shows how the nationalities are distributed within the personnel categories of Nikhef.

TABLE 10 **Percentage of Nikhef staff with a non-Dutch nationality, in 2011 and 2016**

	2011	2016
Scientific staff	21%	27%
Postdocs	72%	83%
PhD students	48%	53%
Technical staff	5%	11%
Support staff	6%	3%

These figures do not make it necessary to implement specific policies aiming at cultural diversification. Nonetheless, standing non-discriminatory policies are embraced and executed during *e.g.* recruitment processes.

Age Diversity

The age distribution within Nikhef as a whole does not show notable developments over the review period. Still, it is worthwhile to elaborate on the distribution per function category.

TABLE 11 **Development of age distribution per function category at Nikhef**

2011	**<30**	**30-39**	**40-49**	**50-59**	**>60**
PhD students	89%	10%	0%	1%	0%
Postdocs	39%	58%	3%	0%	0%
Scientific staff	0%	21%	36%	24%	19%
Technical staff	5%	23%	16%	32%	24%
Support staff	0%	32%	32%	36%	0%
Nikhef total	**28%**	**25%**	**16%**	**19%**	**12%**

2016	**<30**	**30-39**	**40-49**	**50-59**	**>60**
PhD students	82%	17%	0%	1%	0%
Postdocs	10%	77%	13%	0%	0%
Scientific staff	0%	8%	42%	26%	24%
Technical staff	4%	26%	15%	32%	23%
Support staff	7%	17%	31%	21%	24%
Nikhef total	**27%**	**23%**	**19%**	**17%**	**14%**

Remarks can be placed on the following subjects:

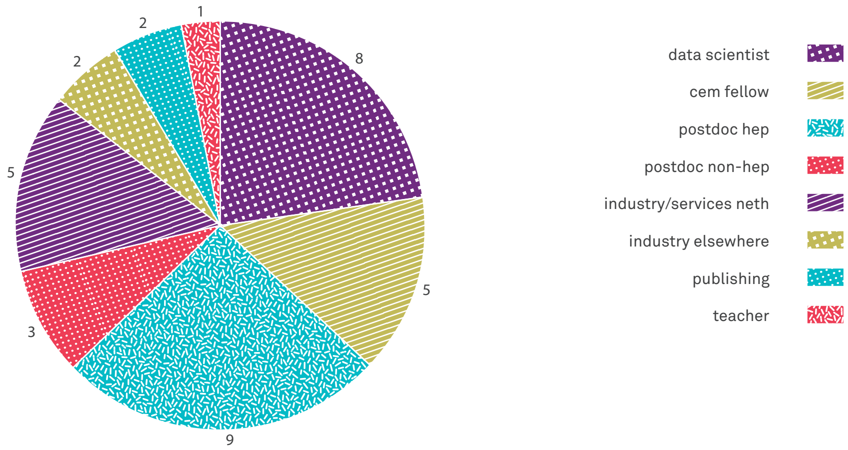
- → The age of postdocs shows a tendency to increase. This is part of a broader trend in science, since permanent positions in science are scarce (due to shrinking long term budget perspectives), while the pool of ambitious and talented scientists who pursue a long term career in their research field is relatively large.
- → The average age of support staff members has increased. Nikhef has recognized this trend and has an active approach on both keeping elder staff employable with training programmes, and replacing retiring support staff members by candidates with a less experienced profile.

Education & personal development

Nikhef aims at a level playing field for all its employees in terms of compensation and benefits, education and personal development opportunities. For example, the highly valued 'soft skills-courses' that are offered to PhD students in NWO-I service, are also made available to university employed PhDs. These courses do not only aim at scientific writing and presenting scientific work, but also focus on 'giving shape to your career', in which PhD students actively explore their future possibilities on the labour market. Whenever desired, additional coaching and support is offered.

As a result, many Nikhef PhD graduates easily succeed in finding jobs following their defence. Although we lack exact figures on employment of all Nikhef alumni, Figure 2 provides data on the sectors in which the (35) PhD students graduated in 2014 and 2015 have found jobs. Another indication of the success on the labour market of Nikhef is the amount of unemployment benefit that is paid to former Nikhef employees each year. The past 4 years this amount fluctuates around 100 k€ per year. With on average 35 employees leaving Nikhef every year, this means about 3 k€ of unemployment benefit cost per employee leaving Nikhef: less than one month's salary.

FIGURE 02 **Breakdown of jobs of PhD students graduated in 2014 and 2015**



Another subject Nikhef stimulates and supports is the writing of grant proposals by our scientists. Courses and coaching are offered, and scientists who are actually submitting proposals are offered help by experienced peers, and professional coaching. The support is offered to all scientists planning to submit grant proposals, regardless of their employer.

Apart from the general education budgets, that were in majority centrally allocated at NWO-I, Nikhef has created budget room for a diversity of customized trainings, courses and coaching for employees willing to develop themselves.

Finally, Nikhef currently offers three of its technical staff members the opportunity to pursue a PhD program.

FUNDING AND EXPENSES

The Nikhef income has increased over the course of 2011 to 2016 (from 26 M€ to 34,5 M€). Inflation in this period (CBS index) has been a little over 9%, implying that about 6 M€ has been 'real' growth. More than half of this increase is attributable to university groups and staff joining Nikhef, in particular the recent joining of University of Groningen. The university groups now form about 20% of the total effort. The rest of the real increase is therefore attributable to Nikhef's successes in obtaining additional funding from various sources. In a one-liner: *each euro of Nikhef's base funding generates another euro in additional funding.*

TABLE 12 **Funding 2011 - 2016**

Funding (M€)	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
FOM institute/mission	11.989	11.274	11.390	11.844	11.526	12.289
FOM institute/programme	2.767	2.647	2.656	3.519	3.668	3.360
FOM university groups	1.806	1.678	1.551	299	741	926
Universities	3.453	3.913	4.202	4.828	5.033	6.882
Additional funding	5.942	6.740	10.266	7.675	8.490	11.047
Total	**25.957**	**26.252**	**30.065**	**28.164**	**29.458**	**34.504**

The tight mission budget has forced Nikhef in the recent period to be very careful with committing to permanent positions, both scientific staff and technical and engineering staff. It explains why the NWO-institute had so few occasions to appoint permanent scientific staff and it has been one of the reasons to instate the flexible shell in our technical and support groups as explained in the previous section on personnel.

The remainder of this chapter explains the Nikhef funding situation in more detail. We use a 10 year time frame (2007 - 2016) to deal with preceding funding and expenses trends affecting the current evaluation period.

Funding 2007-2016

The joint research programme of the FOM-institute Nikhef and the participating university groups is funded by four separate sources. The first source is the 'base'[2] funding for the FOM-institute: the sum of the programme budget and the mission budget. The second source is the FOM funding for the university groups (RU, UU, VU and since 2016 also the RuG), which are part of Nikhef (historically the FOM funding for the University of Amsterdam, is considered to be included in the institute's budget). The third source is (the equivalent in money of) the personnel and material budget of the university groups. The fourth source represents any form of other funding: project funding, acquired (mainly) by the FOM-institute, from third parties (such as the EU, NWO, the Ministry of Economic Affairs), contract research and other activities.

Base funding: mission budget and programme funding

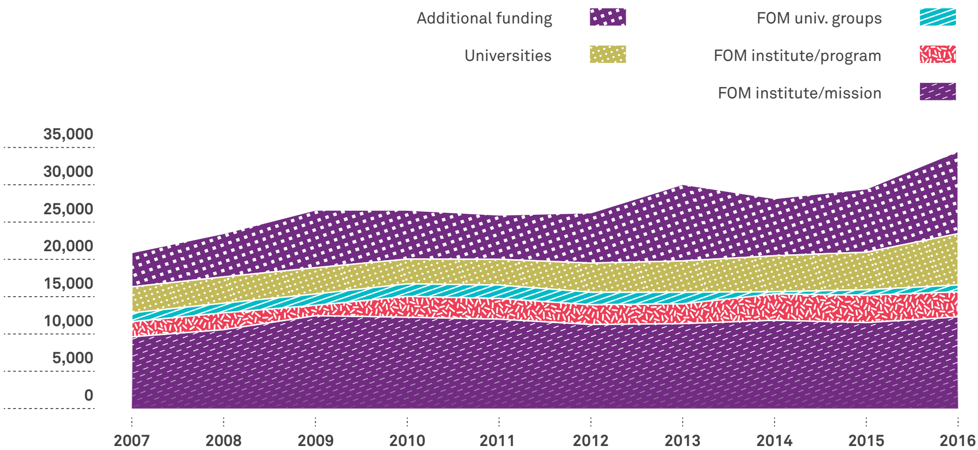
The base funding for the institute has increased in the period 2008-2011, due to both an increase in the mission budget and the programme budget. The mission budget has been raised permanently by FOM with about 0,5 M€, after the excellent result of the mission evaluation in 2007. NWO has for the same reason temporarily provided 0,45 M€ annually for the years 2008-2010. Another temporary increase from NWO regarded a 'dynamization' impulse by NWO in which 3,4 M€ was allotted to Nikhef, spread over the years 2009–2011.

Also new FOM programme funding has been acquired: Theory (2008-2013: 1,5 M€), Cosmic Rays (2008-2013: 3 M€) and for Gravitational Physics (2010-2015: 2,1 M€). However, due to budget cuts applied by NWO to FOM, Nikhef's mission budget as provided by FOM has decreased again as of 2012. This has been partly alleviated by a (first temporary and now permanent) contribution of 0,5 M€ to the Nikhef mission budget in the

[2] The word 'base' is not very appropriate anymore for the 'programme' part of the funding, since Nikhef had to compete for programme funding since 2008.

context of the 'Topsector' policy (see chapter 5). In 2016 the mission budget has increased again to compensate for a general salary increase (as negotiated between employer and unions).

FIGURE 03 **Funding 2007-2016** (in k€)



The *programme* funding for Nikhef has been more or less fixed due to the fact, that FOM has in 2012 decided to maintain a ceiling for the sum of Nikhef's mission and programme funding. The institute still had to apply for programmes, for which the funding -if approved- could not go beyond this ceiling. The good news is that Nikhef has indeed succeeded in acquiring all funding up to the ceiling amount. Almost all of the available programme funding has been filled by the grant for the LHC-physics programme, which runs from 2014 till 2021. Administratively this programme is completely granted to and run by the FOM-institute; this explains the stepwise decrease in the category *'FOM-univ. groups'* funding in Figure 3. This has been done in the context of streamlining, strengthening and simplifying the administrative control of Nikhef's (experimental) activities by the institute management.

Other granted programmes have been for Dark Matter searches (2 M€, 2013-2018), Quantum gravity (Theory: 1,2 M€, 2014-2018), Higgs physics (Theory: 2,1 M€, 2015-2020), Observing the Big Bang

(Theory: 2,3 M€, 2015-2020) and Gravitational Wave detection (1 M€, 2016-2020). It should be noted that for the Theory programmes the funds granted to the university groups do *not* count as part of the amount limited by the ceiling. The most recent success has been the approval of the new programme on electron Electric Dipole Measurements (eEDM) from our new University of Groningen partner. This programme runs from 2017 onward, so is not part of the current evaluation.

FOM funding university groups

The FOM funding for the university groups has decreased as of 2014, but this is due to the administrative change mentioned above. What remains in this category are the funds for the theoretical programmes and projects as granted by FOM.

University funding

After a slight decline until 2011, the university share in Nikhef has increased again, both due to staff appointments and to additional staff joining Nikhef such as Falcke, Hörandel and Nelemans (Nijmegen - Astronomy), for 50% as of 2012, Loll, Saueressig (Nijmegen - Theory) as of 2013, Bertone (2011) and Berge (2013), both UvA (Dark Matter theory and ATLAS respectively), each for 50%. The largest increase has obviously taken place in 2016 with the addition of the Van Swinderen Institute (Groningen), bringing effort in Theory, LHCb and a new activity in eEDM, in total quantified to almost 2 M€.

Additional funding

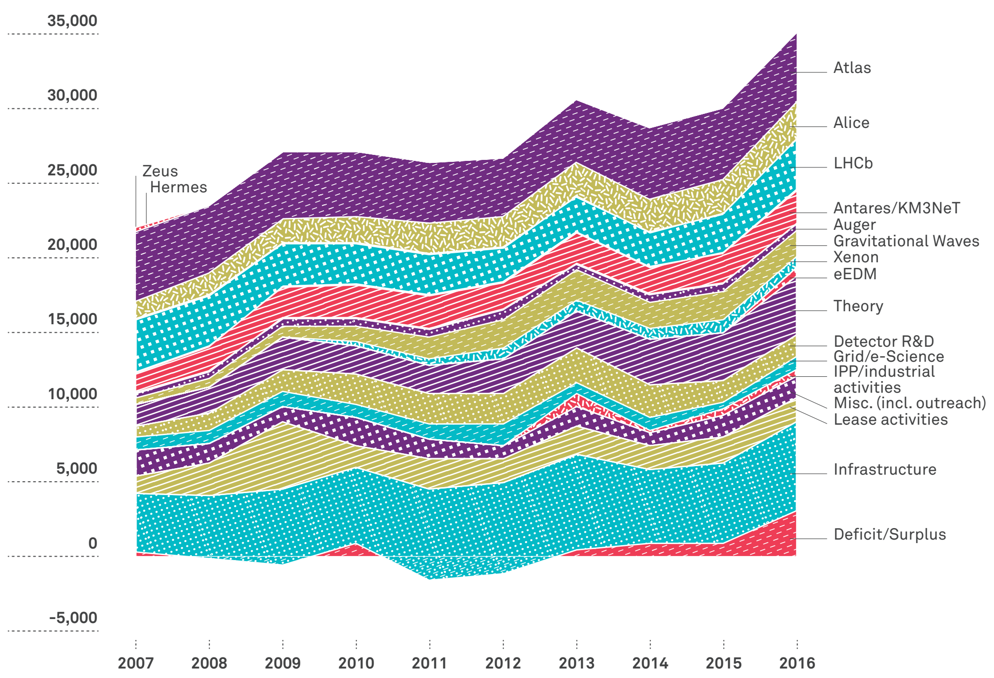
Nikhef has been increasingly successful in acquiring support from external funds. This fourth source of money shows a significant increase: from about 1,3 M€ in 2000 (representing 8% of the total funding) to 11 M€ in 2016 (32% of total funding). This increase is due to successes in obtaining project funding from FOM, from '*Vernieuwingsimpulsen*' (NWO), from ERC (Advanced) Grants, EU Training Networks and MSC fellowships (Theory, Detector R&D), from other EU sponsored projects (notably on grid and other computing activities and on astroparticle physics) and from Nikhef's role in the Dutch national e-infrastructure (a continuation of the successful BiG Grid project: 2007-2012).

Another sizable source is the turnover from the lease of the former accelerator buildings and from the datacenter activity: housing customers of the Amsterdam Internet Exchange (AMS–IX) and other internet service providers. Especially this last source has shown an increase in turnover from about 0,5 M€ in 2000 to about 3.3 M€ in 2016.

Expenses

Figure 4 shows the distribution of costs over the joint research activities during the evaluation period. Expenses have by and large matched funding, with (slightly positive and negative) exceptions in various years. 'Expenses' in activities are defined as directly attributable costs. All other costs (which are by definition not directly attributable) are defined as 'infrastructure' costs. These indirect costs are at a relative stable level of around 20%.

FIGURE 04 **Expenses 2007-2016** (in k€)



The 10-year graph starts at just the end of the two research activities at HERA-DESY (ZEUS and HERMES), and at the start of the gravitational waves detection activity. As of 2008 the three activities shown at the top of the graph are the LHC-experiments, roughly at a stable level of about 41% of direct cost. In the last five years the astroparticle physics have grown, now reaching the 20% level of direct costs, which nicely fits the ambition of the current Nikhef strategy having a 2:1 ratio between those two lines.
The enabling activities (Theory, Detector R&D and Grid) together make up 26% of direct cost and outreach, contract research and miscellaneous activities comprise 7%.

The datacenter activities (both for the internet exchange and the grid activities) require a basic maintenance budget and from time to time investments in upgrading and expanding the facilities. Over the years 1997-2016 the total datacenter turnover has been 35,6 M€ and the operating and investment cost has been 21,3 M€. The largest and most prominent upgrade has taken place in 2009/2010, for a total of around 5 M€. In 2016 the datacenter operating cost is at the level of 6% of Nikhef's total direct cost. The net result from the datacenter activities (currently almost 2 M€ annually) is reinvested in the regular research activities of Nikhef.

Investments

Table 13 shows the investment budgets as granted to Nikhef in the years 2011-2016. Note that these amounts are not included in the income and expenses graphs shown above. The table shows that Nikhef has an increasing 'turnover' in investments, with an average of 3,6 M€ per year for the given period.

Nikhef can address several channels to fund investments. The first source (labelled 'FOM/M') amounting to 319 k€ per year is under the control of the Nikhef directorate and is used for investments in scientific equipment. It has been used for instance to start investing in Advanced Virgo before additional NWO funds became available.

The second -competitive- source, called 'NWO-groot', is dedicated to investments of the scale of several millions. In the evaluation period Nikhef obtained a 2 M€ grant for investing in Advanced Virgo instrumentation.

The third and most sizable source are NWO funds related to research infrastructures appearing on the national Roadmap for Research Infrastructures (RIs). Under a precursor scheme of this Roadmap fund Nikhef has obtained in 2008 funding for KM3NeT 1.0 (8,8 M€). Recently, in 2014 Nikhef has obtained a 15,24 M€ grant for the Dutch contributions to the LHC detector upgrades and for the continuation of the investments in the Dutch WLCG Tier-1.

As part of an even earlier precursor of Roadmap funds Nikhef together with partners NCF (National Computing Facilities) and NBIC (Netherlands Bioinformatics Centre) obtained in 2006 a large grant (the BiG Grid-project) for the roll-out of a distributed computing infrastructure in the Netherlands. The total grant was 28,8 M€. In Table 13 only the amount of this is mentioned that has resulted in investments in equipment at the Nikhef datacenter. BiG Grid ran from 2007 to 2012. As of 2013 investments in the Nikhef datacenter are part of the funding for the Dutch national e-infrastructure, coordinated by SURF, in which Nikhef is a partner.
See the appendix for a detailed overview of all grants.

TABLE 13 **Investments**

Sources	**Investments (k€)**	**<2011**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
FOM/M	Computing							
	Workshops					319	319	319
	R&D							
	KM3NeT							
	Advanced Virgo		286	444	444			
	Auger					450		
NWO Roadmap	ATLAS					120	250	450
	ALICE						1.350	1.950
	LHCb						500	1.650
	Computing					500	1.170	230
	KM3NeT	1.010	1.420	1.970	1.710	1.800	450	440
NWO-Groot	Advanced Virgo			900	1.000	100		
NWO	BiG Grid	2.220	750	200				
SURF(sara)	NL e-infrastr.				410	320		144
	Total		**2.614**	**3.514**	**3.564**	**3.609**	**3.189**	**5.039**

OUTPUT

In the 2011–2016 review period, Nikhef published 2243 refereed citable scientific articles in international journals, according to the SPIRES-HEP database, and 130 PhD degrees were awarded.

The production counted per year by the experimental groups increased when data taken at the LHC became available (see Figure 5). Also shown are a detailed breakdown of the scientific publications (Figure 6) and a breakdown per experiment of theses and publications in Table 14. The differences between the number of SPIRES database entries and that as counted by the experimental groups in Table 14 are due to differences in determination of publication dates, missing journals in the SPIRES database and conference contributions not counted in this selection of the SPIRES database. Note that nowadays most conference papers are refereed and published under the responsibility of the conference organisations.

FIGURE 05 **Number of scientific refereed publications in the last seven years**

split in: accelerator based physics (LHC), non-accelerator based physics (Neutrino Telescopes, Grav. Waves, Dark Matter, Cosmic Rays, Astr. Phys.) and other (Det. R&D, Theory, Physics Data Processing and Miscellaneous)

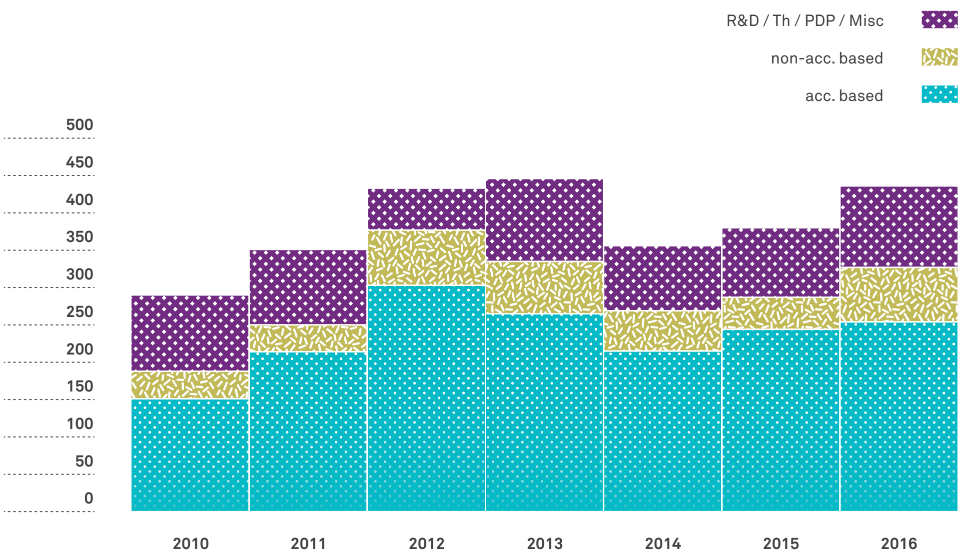
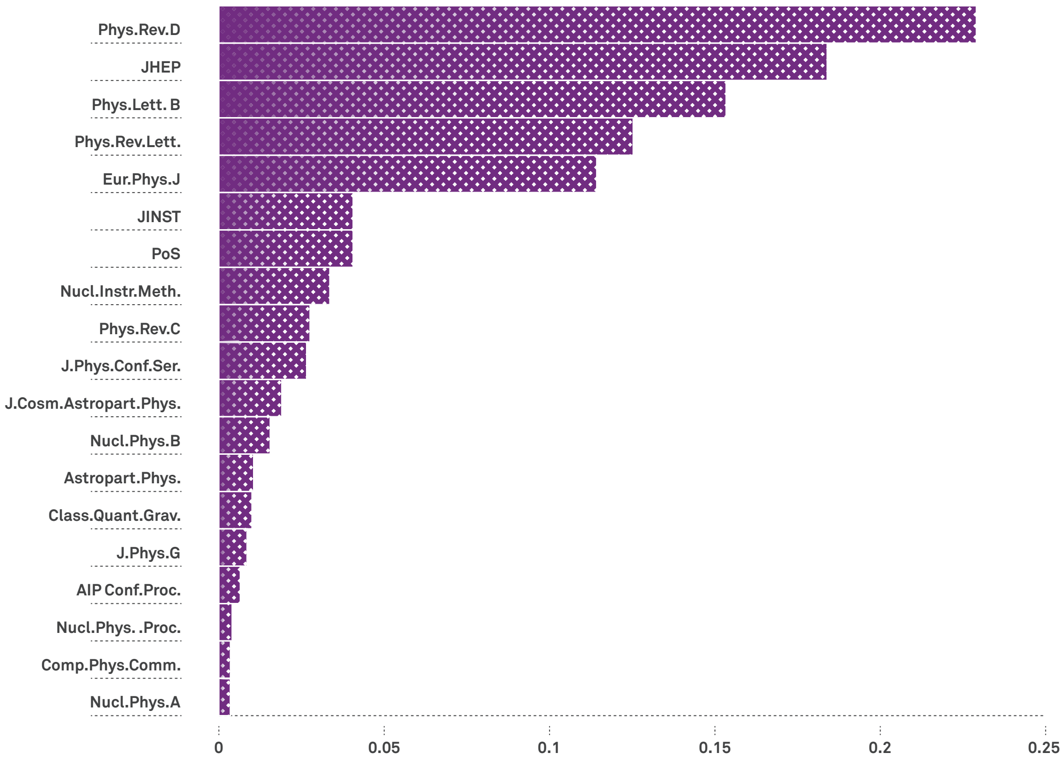


FIGURE 06 **Breakdown of publications in relative fractions per journal**



Typically, experiments in a building phase produce relatively few papers per year, on design studies, hardware, electronics, and beam tests. Running experiments produce a large number of papers per year. Apart from papers in scientific journals, specific contributions of Nikhef physicists are documented in internal notes, which are also peer reviewed.

TABLE 14 **Output: breakdown per year and per programme**

		2011	2012	2013	2014	2015	2016	Total
Publications		**351**	**433**	**446**	**356**	**380**	**436**	**2402**
Theses		**17**	**22**	**18**	**15**	**20**	**38**	**130**
ATLAS	Pub	118	173	109	108	135	144	**787**
	Thes	6	8	2	5	7	7	**35**
LHCb	Pub	55	92	124	83	80	63	**497**
	Thes	2	2	2	1	4	4	**15**
ALICE	Pub	41	38	32	24	29	47	**211**
	Thes	1	3	3	2	2	8	**19**
Neutrino Telescopes	Pub	14	10	18	4	6	20	**72**
	Thes	2	1	1	1	1	1	**7**
Gravitational Waves	Pub	14	33	12	23	14	27	**123**
	Thes	2		2		1	2	**7**
Dark Matter	Pub		3	4	3	3	5	**18**
	Thes					1		**1**
Cosmic Rays	Pub	8	16	8	11	8	12	**63**
	Thes	2	1	1			2	**6**
Detector R&D	Pub	16	8	13	5	9	8	**59**
	Thes		2		1	2		**5**
Theoretical Physics	Pub	55	25	75	68	67	77	**367**
	Thes	1	4	6	4	1	5	**21**
Physics Data Proc.	Pub	4	2	4	1	2	1	**14**
	Thes						1	**1**
Astroparticle Physics	Pub		12	28	13	12	9	**74**
	Thes	1			1			**2**
Miscellaneous	Pub	26	21	19	13	15	23	**117**
	Thes		1	1		1	9	**12**

TABLE 15 **The five most cited papers**
(excluding self-citations) in the SPIRES/INSPIRE database (May 2017)

Article	Citations
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ATLAS Collaboration, Phys. Lett. B716 (2012) 1	6300
Dark Matter Results from 225 Live Days of XENON100 Data XENON100 Collaboration, Phys. Rev. Lett. 109 (2012) 181301	1259
Observation of Gravitational Waves from a Binary Black Hole Merger LIGO Scientific and VIRGO Coll., Phys. Rev. Lett. 116 (2016) 061102	1192
First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV [see Glossary for AMS description] AMS Collaboration, Phys. Rev. Lett. 110(2013)141102	588
Combined search for the Standard Model Higgs boson using up to 4.9 fb-1 of pp collision data at √s=7 TeV with the ATLAS detector at the LHC ATLAS Collaboration, Phys. Lett. B710(2012)49	578

RESEARCH INTEGRITY

In particle- and astroparticle physics, research is typically performed within international collaborations of researchers. Since publications are co-authored by all collaborators, a high degree of attention is devoted to the integrity of the process by which results are obtained, and the internal review of these results before they are published.

The collaborations typically require that only validated tools and validated data sets be used in data analysis. Data sets in which a new signal may hide are typically "blinded" to prevent researcher bias. Internal reviews of all results in the collaborations take place at multiple levels: within dedicated physics analysis groups, by review boards composed of experts, and collaboration-wide before publication. The review procedure often demands multiple crosschecks and validation by multiple independent analyses. Surprising results deviating from the prevailing scientific context are scrutinized even more. However, the decision to publish or not does not depend on the agreement or disagreement from expectation: results, regardless of their nature, are published when all co-authors are satisfied that all required checks and balances have been carried out correctly. Researchers, including students and PhD candidates, thus "grow up" within this environment of checks and crosschecks, and learn to make this their scientific culture. Supervision of PhD candidates also takes place within this environment, and PhD students are made actively aware of it. Students are also briefed on the end terms of the PhD thesis and rules on plagiarism. There are no documented cases of fraudulent results published by any (astro) particle physics collaboration.

It is common practice, and even policy for results obtained at CERN, to publish all results in open access journals. Results also appear on the publically accessible arXiv preprint server.

OPEN DATA

The collaboration-mode of doing research also implies that a great deal of attention is given to raw and processed data storage, preservation and distribution. Data must be accessible from all over the world (e.g. through the LHC data processing centers), for very long timescales. The collaborations typically have a policy to store data and tools so that all obtained results can be checked and rederived from the raw data for the foreseeable future, well beyond the lifetime of the experiments. Building on this practice the paradigm of open access to the raw data (typically after a short proprietary period) has rapidly gained ground in (astro)particle physics.
Most experiments have implemented such a policy already; some have opened a fraction of their data for educational purposes. Our research in general satisfies the recent NWO Institute Data Management Policy Framework (2016), which is concerned with many of these aspects.

PHD PROGRAMMES

PhD students at Nikhef are automatically enrolled at the Research School for Subatomic Physics (OSAF). PhD students in the Theoretical Physics department are enrolled in the Dutch Research School of Theoretical Physics (DRSTP).

Through the OSAF and DRSTP institutions the tutoring and supervision are organized and aligned. Also, educational programmes are developed by the two Research Schools. As a result, problems in the PhD trajectory are usually flagged relatively early, which offers the opportunity to act in an early stage. Hence, the dropout rate of PhD students at Nikhef is low.

Training programme

In the PhD phase, students have to attend six topical lectures. These are three-day intensive courses, taught by scientists from the OSAF or international experts on topics relevant to subatomic physics. Each of the first two years PhD candidates attend a two-week summer school that is jointly organized between Germany, Belgium and the Netherlands[3]. The third year an international school is attended. In principle the candidate can propose a school provided it is a good match with the research programme and at the appropriate level. A majority chooses to attend the CERN European school of physics. Others have opted in recent years for schools at the Stanford Linear Accelerator Center in California, at Fermilab near Chicago, in Mexico and in Colombia.

Next to the scientific training, students can follow a number of courses. FOM (now NWO-I) organizes a number of courses for PhD candidates:

- → Taking charge of your PhD project (obligatory)
- → The art of presenting science
- → Being successful in Dutch organizations
- → Business Orientation Week (Nyenrode Business University)
- → Write it right (scientific writing skills)
- → Teaching and Learning

Supervision

Students typically have a daily supervisor and a thesis advisor. The latter always is a professor at the university that will award the PhD degree. At the beginning of the PhD a training and supervision plan is prepared. This specifies, in which experiment the student will work, who are the thesis advisor and daily supervisor, how frequently the student meets with his advisors, with a minimum of twice a month, and which courses will be part of the PhD training. The training and supervision plan is discussed with the student before it is signed.

[3] http://bnd-graduateschool.org/

Progress is monitored in progress interviews. The student, the supervisor(s) and an independent member of the Education Committee of OSAF or DRSTP (together called C3-committee) meet and discuss the progress of the thesis work, training of the student future plans and evaluate if the supervision is adequate. Progress interviews contain both a look at past performance and a discussion of future steps. Interviews are held after 6,12, 24, and 36 months. The independent member of the Education Committee reports at the meeting of the full committee on the progress of the student. When the 6 months interview leads to serious doubt about the students' ability to complete the PhD, progress can be monitored more closely and a go/no-go decision could be taken within the first 12 months. The independent member can also advise to replace the supervisor in case of problems with the supervision. Students are also briefed on the end terms of the PhD thesis, rules on plagiarism, and advice for a timely completion of the PhD thesis.

TABLE 16 **Enrolment and success rates in the PhD programme**

Enrolment				**Success Rates**											
Starting year	Enrolment (male/female)			Graduated in year 4 or earlier		Graduated in year 5 or earlier		Graduated in year 6 or earlier		Graduated in year 7 or earlier		Not yet finished		Discon-tinued	
	M	F	Total	#	%	#	%	#	%	#	%	#	%	#	%
T-8 (2008)	14	5	19	2	11%	10	53%	2	11%	2	11%	0	0%	3	16%
T-7 (2009)	12	6	18	2	11%	11	61%	3	17%	1	6%	1	6%	0	0%
T-6 (2010)	14	4	18	4	22%	5	28%	7	39%	2	11%	0	0%	0	0%
T-5 (2011)	16	2	18	2	11%	14	78%	2	11%	0	0%	0	0%	0	0%
T-4 (2012)	16	3	19	6	32%	5	26%	0	0%	0	0%	8	42%	0	0%
Mean					**17%**		**49%**		**15%**		**5%**		**10%**		**3%**

Internal quality assurance

Students provide feedback after each topical lecture and summer school. This feedback is discussed in the Education Committee and used to improve the quality of the lectures. As mentioned before, the C3 interviews are the main instrument of quality control. In the interview the student gives feedback on several aspects of her/his PhD program, like scientific progress, supervision, training needs and teaching load. The international scientific advisory board (SAC) also discusses the OSAF and makes recommendations. Nikhef has an employees' council with two OSAF PhD candidates as members to provide feedback on employment matters.

Typically, 15–20 theses are produced per year, however the extraordinarily high number of PhD theses in 2016 is due to the expansion of Nikhef with the Van Swinderen Institute of the University of Groningen. In Figure 7 the PhD duration in 2016 is shown, with a median of 55.2 months. Outliers in the distribution often have to do with the difficulty of finishing a thesis when already employed elsewhere. The median per year is shown in Figure 8.

FIGURE 07 **PhD duration in months from start employment till PhD graduation in 2016**

(Van Swinderen Institute excluded). The median is 55.2 months. Note that there is a 3-4 months' delay between finishing the thesis and the thesis defense

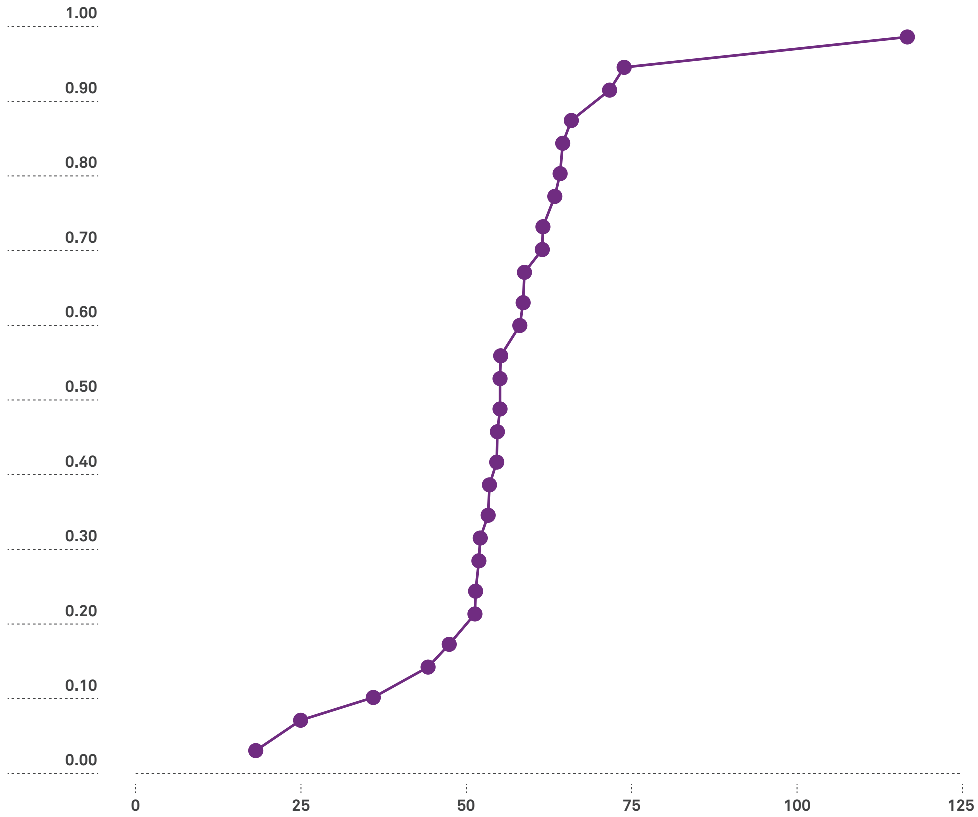


FIGURE 08 **Median of PhD duration in months for the years 2001 - 2016**

RELEVANCE TO SOCIETY

The 2011 evaluation panel endorsed the Nikhef mission and recommended to include its valorisation activities as an explicit part of it. This has indeed led to the inclusion of the following phrase in our mission: *The research at Nikhef relies on the development of innovative technologies. The knowledge and technology transfer to third parties, i.e., industry, civil society and general public, is an integral part of Nikhef's mission.*

Our outreach and knowledge and technology transfer activities are described in this chapter. Outreach highlights are the extensive media coverage about the discovery of the Higgs boson and the first detection of Gravitational Waves, including the countless talks and articles in the popular press following these two major events. Regarding knowledge and technology transfer we highlight the activities around our spin-offs, our CERN-BIC and the various research collaborations with industry.

OUTREACH AND COMMUNICATION (IN TIMES OF TWO BIG SCIENTIFIC DISCOVERIES)

The last years saw no less than two major scientific discoveries in the field of particle and astroparticle physics, and Nikhef was part of both of them. Nikhef scientists made vital contributions to the discovery of the long-sought Higgs particle in 2012 as well as to the first direct detection of gravitational waves announced in 2016. Both breakthroughs had huge impact also in terms of outreach and communications. We refer to the two narratives in this document for an account of how those scientific discoveries translated into societal impact.

Not only in the context of big discoveries, but as a matter of principle, Nikhef puts much effort into outreach and communications activities every year in order to share all its research not only within the scientific community but also with societal target groups, in this way contributing to the relevance of Nikhef's research work to society. The main target audiences Nikhef engages with are: the general public, the media (as multiplicator to reach the general public), science and technology decision makers, and potential industrial partners.

A more detailed overview of outreach and communication activities can be found in the appendix.

EDUCATION

Nikhef attaches great importance to inspiring and training young people. To this end, Nikhef offers various programmes for school children and their teachers, as well as a thorough education for bachelor, master and PhD students. Between 2011 and 2016, the following programmes were organized or supported by Nikhef.

Primary school children

Nikhef participates in the organisation of the annual national science tournament for primary school children "Techniek Toernooi", in which children between 4 and 12 years compete on technical constructions and experiments. Nikhef staff is part of the jury that assesses the designs. Furthermore, several Nikhef scientists presented a lecture in the popular series "Wakker Worden Kinderlezingen" for children between 8 and 12 years at the NEMO Science Museum, or visited primary schools for individual lectures.

Secondary school students

Nikhef offers secondary school students many opportunities to get introduced to particle and astroparticle physics. Between 2011 and 2016, many school groups with in total more than 1300 students visited Nikhef for an afternoon programme consisting of a lecture, film and guided tour. Moreover, Nikhef scientists visited many schools to give individual lectures at their locations. Nikhef also supported numerous CERN visits of secondary school students by providing Dutch guides for tours. 124 students were helped by Nikhef scientists to carry out their 'profielwerkstuk' (dedicated science project in their final secondary school year). Every year, Nikhef organises one-day International Masterclasses on Particle Physics in collaboration with IPPOG (International Particle Physics Outreach Group), in which about 330 students participated between 2011 and 2016. Since 2016, a Masterclass on cosmic rays is held in addition to the particle physics one, in which 17 students participated.

HiSPARC

Nikhef is furthermore in charge of the central coordination of HiSPARC (High School Project on Astrophysics Research with Cosmics), which is a collaboration between scientific institutes and universities founded in 2002. HiSPARC offers secondary school students and teachers an opportunity to participate in a real scientific experiment. The students build their own cosmic-ray detection stations that they install on the roof of their schools, and subsequently carry out research with data from their own as well as from other stations in the network. By 2016, the HiSPARC detector network has grown to about 140 stations, most of them in the Netherlands, but several also in the UK and in Denmark. About 1000 secondary school students take part in the HiSPARC programme per year.

Secondary school teachers

Nikhef also invites secondary school teachers to refresh and deepen their knowledge of particle and astroparticle physics and offers teachers the opportunity to experience state-of-the-art research themselves. By motivating teachers, their enthusiasm is passed on to their students.

Together with CERN, Nikhef organises an annual four-day Dutch CERN teacher programme, in which 118 teachers participated between 2011 and 2016. 35 teachers took part in the teacher-in-research programme ('leraar in onderzoek'), made possible by several sponsors (FOM, Nikhef, Sectorplan Natuur- en Scheikunde, etc.) enabling them to spend one day per week during a school year on doing their own research project at Nikhef within the HiSPARC programme. Furthermore, several courses and network meetings on (astro-) particle physics were organised for teachers by Nikhef in collaboration with universities and other partners, reaching more than 150 teachers. Nikhef scientists also regularly gave lectures and (HiSPARC data analyses) workshops at the annual national conference for physics teachers, organised by the Working Group Didactics of Physics.

TABLE 17 **Secondary School Projects**

Programme	# participants (2011 - 2016)
Secondary School Students	
Visit Nikhef	About 1300
Masterclasses	About 350
'Profielwerkstuk'	124
Secondary School Teachers	
Dutch CERN teacher programme	118
Teacher-in-research programme	35
Courses and network meetings	About 150

Bachelor students

Nikhef is also involved in education at bachelor level. Many staff members have appointments to lecture in bachelor programmes at Dutch universities. In addition, Nikhef staff organises several research and laboratory classes, for about 30 students per year.
Furthermore, on average seven students per year are supervised by Nikhef scientists for their final-year bachelor project on Nikhef-related research.

Master's programme at Nikhef

All five partner universities (UU, UvA, VU, RU and RUG) offer a two-year Master's programme focused on the (astro-)particle physics research done at Nikhef. In the first year, the programme typically consists of lectures on particle and astroparticle physics. These lectures include a solid introduction to the Standard Model, physics Beyond the Standard Model, Cosmology, Quantum Field Theory, General Relativity, CP violation, Gravitational Waves, etc., as well as advanced experimental methods like Statistical Data Analysis, Particle Detection, and a C++ course. The various aspects of experimental particle physics are combined in a semester-long project, called the Nikhef Project. During their second year, the students work on their own research project in one of the physics groups at Nikhef. At the beginning of the 2016/2017 academic year, the UvA and VU MSc programmes were officially integrated into a fully joint degree.

Furthermore, all master students in the two-year GRAPPA (GRavitation AstroParticle Physics Amsterdam) joint UvA-VU programme follow Nikhef's particle physics lectures, and about half are expected to also do a research project at Nikhef in Amsterdam. Besides the students from the five partner universities, about 10 students from non-partner universities (e.g., Leiden, Twente, Delft) have also done their master research project at Nikhef in the period 2011-2016.

TABLE 18 **MSc student cohorts in the UvA/VU university (astro)particle physics programme**

In the period 2005-2010 the percentage women was 19%, the percentage international students was 16%

Cohort	Female	Male	Total	International
2011	1	8	9	1
2012	3	9	12	3
2013	0	9	9	3
2014	4	12	16	3
2015	2	3	5	2
2016	7	25	32	10
Total	**17 (20%)**	**66 (80%)**	**83**	**22 (27%)**

KNOWLEDGE AND TECHNOLOGY TRANSFER

Nikhef's primary focus is and will always be curiosity driven research, pushing the boundaries of fundamental knowledge. However, Nikhef has always acknowledged the importance of industrial applications and societal gains from fundamental research ('*valorisation*'). Nikhef has concentrated in the 2011 - 2016 period its efforts on the following action lines:

- stimulating the context for setting up *spin-offs* based on our technologies;
- expanding research efforts with third parties (industry);

Our *spin-off* policy, which has started in 2011, and includes the establishment (in 2014) of a CERN-Business Incubation Centre (CERN-BIC) has by now resulted in four companies (one of which has already ceased to exist). Although two of the spin-offs are very close to important next investment steps, we consider it too early to already qualify the policy as successful. Aspects of the policy, such as the role of *shareholder*, have proven to be cumbersome.

Regarding our research efforts with industry: these definitely have increased, partly due to the national *Topsector policy*. However, this remains a challenging endeavour, because it requires a genuine interest from Nikhef and the company in a common research goal. This almost always regards technology driven collaboration. Simply put: industry is never interested in discovering the Higgs boson or Gravitational Waves with us, but is interested in the technologies we use to accomplish that.

Of course Nikhef cherishes its existing successful market oriented activities, in particular regarding our datacentre. In terms of financial value the *Nikhef datacentre* can be considered the single most valuable valorisation asset. It generates currently a turnover of 3,3 M€ a year with an operating cost of about 1,3 M€. Through its history as an Internet Exchange hub the datacentre has maintained a high rank (around #15) on the worldwide connectivity list, housing around 150 connected networks. From a recent acquisition by a third party of a comparable datacentre on the Amsterdam Science Park it is not farfetched to estimate the market value of the Nikhef datacentre to be several tens of millions of euros.

Patents

Nikhef currently owns or co-owns 8 patents, of which 7 have been submitted in the 2011-2016 time frame. Half of the patents are (in the process of being) licensed. Details can be found in the appendix.

The spin-off activities and industry research collaborations are described in some more detail below.

Spin-off policy

In the 2011-2016 time frame Nikhef has developed a policy regarding a particular form of valorisation: the creation of *spin-offs*. Early 2011 Nikhef management felt, that for the involvement of Nikhef in making a spin-off into a success, a position as shareholder might be advantageous. In the same spirit we decided to also allow qualified Nikhef-employees to acquire shares in such an enterprise – under well-defined conditions. This has resulted in the establishment of an investment company, called *Particle Physics Inside Products* (P2IP bv). P2IP bv has taken shares in three spin-offs: *Sensiflex* (alignment technology), *Amsterdam Scientific Instruments* (photon detection) and *Omics2Image* (mass spectroscopy). In 2013 ASI and Om2I have merged in a new company ASI Holding (ASIH). In 2013 another spin-off has been established, *Innoseis* (seismic sensoring). P2IP has no shares in this company, but Nikhef has a license agreement including royalty payments. In the appendix the activities of the Nikhef various spin-off companies, whether or not with shares owned by P2IP are described, including a list of associated awards and prizes.

In the context of this emerging spin-off policy Nikhef has in June 2014, at the occasion of the CERN60 event in Amsterdam, signed an agreement with CERN, on the establishment of the *CERN Business Incubation Centre (BIC) at Nikhef*, aimed at helping entrepreneurs to develop and bring to the market technologies emerging from subatomic physics. Located adjacent to Nikhef, entrepreneurs can make use of CERN and Nikhef facilities and of the services of our partners: Amsterdam Venture Lab and the Innovation Exchange Amsterdam (i.e. the Technology Transfer Offices of the two Amsterdam universities). Since its inception the *CERN-BIC* has received two Expressions of Interest (EoI). The first regarded the plans for establishing

a company (working title 'Particle Toys') for selling products serving outreach purposes in subatomic physics, such as a muon lifetime measurement setup and a 'do-it-yourself' interferometer. The viability of this idea is now tested with selling a small series of products at exhibitions and conferences.
The second EoI concerns a plan for establishing a company for setting up and maintaining a platform for FPGA professionals to exchange FPGA codes, and assist in and consult on their development. In the course of 2016 the plan has been further developed. Next steps are expected early 2017.

Contract research and collaboration with industry

Table 19 lists the most important industrial research collaborations in the 2011 - 2016 time frame.

TABLE 19 **Research collaborations and contract research**

Company	Topic / status
Shell	Collaboration centered around the development of ultralow-power seismic sensors. This has resulted in a series of projects under a research collaboration agreement (including the Nikhef spin-off Innoseis) and additionally in an STW project for developing a dedicated ASIC for the readout of these sensors. The total cash and in-kind contribution of Shell in the period 2013- 2016 has been around 1,5 M€.
PANalytical	Long standing research collaboration with PANalytical, around the Medipix technology, resulting in the inclusion of Medipix 2 and Medipix 3 chip technology in the X-ray analysis equipment sold by PANalytical. One of the biggest success stories of bringing CERN technology to the market. PANalytical regularly uses (and pays for) Nikhef facilities (clean room, bonding machine) and manpower for the assembly of their detectors. The company has also been partner in several publicly funded research projects with Nikhef (Relaxd, Hidralon). Currently a new proposal on increased energy resolution pixel chip development is in preparation.
ASML	Several contract research agreements with Nikhef, first around cooling technology, recently around alignment solutions. Details cannot be disclosed. Currently no new initiatives are in sight.
Tata Steel	A project evaluating the viability of muon radiography for the analysis of the homogeneity of large vessels with (liquid) steel. Currently discussions are ongoing for a follow-up project.

CONTINUE →

Company	Topic / status
Photonis	Interested in co-developing a new type of photo multiplication device ('Tipsy') in the context of the ERC Advanced Grant project 'MEMBrane'. Also interested in another patented development started at Nikhef, microHV. Currently Photonis funds a test setup for such a microHV system.
Hardware vendors	Vendors such as Intel, Dell, Fujitsu, IBM, Mellanox and Juniper regularly use the Nikhef Physics Data Processing (PDP) group as beta-tester of their ICT equipment, based on Nikhef's expertise in developing and operating large-scale computing facilities (including part of the Dutch WLCG Tier-1).

The increasing importance of relations with industry has led Nikhef to appoint a dedicated person as 'Coordinator Industrial Contacts'. This role entails the whole spectrum of contacts with industry:

- → industry as supplier of products and services to Nikhef and to CERN; this includes therefore the role as CERN Industrial Liaison Officer (ILO), whose task it is to position Dutch industry for purchase orders from CERN; in 2011-2016 our CERN-ILO also served as the chairman of the Dutch network of ILOs (ILOnet). The activities are described on www.bigscience.nl and entail among others the organization of events such as 'Holland at CERN'.
- → industry as user of Nikhef expertise and facilities, in the form of contract research;
- → industry as partner in collaborative research projects.

In recent years Nikhef has used the annual Hannover Messe to showcase its technological potential, also inspired by the fact, that the Messe is frequently visited by Dutch government representatives (ministers, state secretaries), providing a perfect stage for media attention.

GRAVITATIONAL WAVE DETECTION: HOW SCIENTIFIC SUCCESS STORIES CAN LEAD TO NEW BUSINESS OPPORTUNITIES

By George van Hal

It was the biggest scientific breakthrough of 2016: the discovery of gravitational waves. Hunting these elusive space-time ripples wasn't just a pathway to sweeping scientific success, however. It also proved a fertile basis for a lucrative new start-up.

Proving a 100 year old prediction by none other than Albert Einstein isn't an everyday occurrence, not even for the physicists at Nikhef, where gathering new insights into the fabric of reality is part of the job description. The first direct detection of gravitational waves was the biggest scientific breakthrough of 2016. The discovery led to massive media attention. From the front pages of newspapers around the world, to television news items, major talk shows and in-depth stories in popular science publications, gravitational waves were everywhere in the days after physicists announced their discovery.

Telling this story, by no means an easy sell for a general public, proved a communications triumph in every sense. Apart from the initial media storm, it gave rise to lasting new communications and outreach opportunities, like the Do It Yourself interferometer Nikhef's Mechanical Engineer Eric Hennes offered to schools and other interested parties to get a better grip on how gravitational wave detectors function.

Still, the interest from both the media and general public in gravitational waves wasn't that surprising when one considers the enormous impact of the discovery. The ability to measure these waves wasn't just the first detection of this highly elusive phenomenon, or the first time anyone saw black holes in action. The detection also opened up a new window on our universe. A window through which physicists might finally be able to unlock our galaxies' most persistent mysteries.

The success story of the gravitational wave detection doesn't just stop at the scientific achievements and the potential for earth-shattering new discoveries, however. As always in science, and certainly at an institute like Nikhef, the way that people from various disciplines work together to solve difficult technological and scientific challenges forms an equally interesting story. Especially when, as in this case, these technological advances create benefits for our society as a whole.

Astounding technological feat

It wasn't surprising that it took physicists so long to prove Einstein's prediction of the existence of gravitational waves. Measuring the very weak effect these waves have on earth requires an astounding feat of technological prowess. For instance: the effect a passing gravitational wave has on earth-based detectors is less than the perturbation created when adding one single drop of water to the IJsselmeer, the large inner sea in the heart of the Netherlands. In other words: the effect that physicists sought to measure was staggeringly small, requiring an highly sensitive detector.

That sensitivity, however, also has a downside. Even the smallest quiver of the earth around the detector might end up distorting a detection. To battle this effect, gravitational wave detectors, so-called interferometers like LIGO and VIRGO, have added suppression mechanisms minimizing the influence of seismic vibrations.
But these seismic vibrations also posed a second challenge. Because a seismic event moves the mass density of the earth, it also temporarily alters the direction of the gravitational pull on the interferometer. It's a very small effect, but it's still something the sensitive interferometer feels.

The only way to combat that effect was to create a network of seismic detectors around the interferometer, accurately measuring the disturbances themselves and correcting for them in the data – a process in which Nikhef's Mark Beker was one of several key players.

The interesting thing, though, is that being able to very accurately measure seismic activity in the ground, isn't only useful for doing science. It's a sought-after skill for all kinds of applications, and as such is also very interesting from a business standpoint. 'Nikhef has a lot of contacts with industries', Beker told popular science magazine *New Scientist* in 2016. 'And during my promotion research, they contacted one of these companies: Shell.'

It turned out that the detection devices Beker and his Nikhef colleagues were studying as part of their research were also very useful in testing geophysical models that Shell was developing. ‘That’s how things got started’, Beker said. The end result was the creation of spin-off company Innoseis, where both Beker and Nikhef’s Gravitational Waves programme leader Jo van den Brand are partners.

Valuable partnership

During the creation of his company, Nikhef was a big help to Beker. ‘The institute offered useful contacts, but also offered a lot of knowledge and support which led to higher credibility for Innoseis’, Beker said. ‘Nikhef has a very positive attitude towards start-ups and entrepreneurship.’

Because of their valuable experience in creating the measurement network for gravitational wave detectors, Innoseis now creates seismic sensors that are smaller, lighter and cheaper than their competition, leading to two official patents and a valuable partnership with Shell. ‘They bought the first 100 of our sensors, which give them a much better sense of what’s happening in the ground.’

And Shell isn’t the only interested party. ‘We’re also working with a number of other companies that are using a network of our sensors to run tests in various locations across Europe, but also in Texas and the Middle East’, Beker says. ‘The end goal is to create large networks of 100.000 sensors. That will allow them to truly see beneath the surface.’

Other than that, Innoseis’ sensors have an obvious usefulness in earthquake detection. But the company is also in talks with police and the military, to explore possible applications. In these areas, the sensors might be used to track people’s movements by using seismic signals to reveal where a person is – or was – walking. ‘Plus, you could use these sensors to pinpoint the location of an explosion’, says Beker.

All of this doesn’t mean that Innoseis’ sensors are no longer being used in gravitational wave detection – they still are. ‘And that’s something that’s very helpful to us, giving us new insights into the way these detectors function. The interaction with the area we started out in is still very important to us.’

Innoseis is, in essence, a perfect example of the way in which the cross pollination of science, society and entrepreneurship leads to better results in both science and business. And because of that, both Jo van den Brand and Mark Beker received valorisation prizes from the former Dutch Foundation for Fundamental Research on Matter FOM (in 2015 and 2014, respectively) for the parts they played.

The next step

And Nikhef’s already planning the next step in this success story. Given their role as an international hub of expert knowledge, Nikhef is currently taking the lead in the next step for gravitational wave research. Van den Brand and his colleagues are setting their sights on Einstein Telescope, which is shaping up to be the European ground-based detector of the future.

Plans for this third generation instrument are already underway, with the southern part of the Dutch province of Limburg emerging as one of the prime candidates for the detector site as a result of its unique geology. 'Einstein Telescope is featured in every roadmap', says Van den Brand. 'The fifth route of the Nationale Wetenschapsagenda (the national science roadmap), has named it game changer number 1, a decision in which people from all kinds of disciplines were involved.'

And while the road ahead for Einstein Telescope is still unclear, it certainly looks promising. Negotiations with governments, universities and local industries are ongoing. 'It's a complicated process', says Van den Brand. 'The only thing that isn't, is the science case.'

One thing's for certain, though. Building a detector on the scale of Einstein Telescope in Limburg will have a large impact on the region – both in jobs and business growth. Designing the detector itself will require new, state of the art science and engineering. In other words: the type of challenge to which Nikhef has proved itself to be uniquely suited. And, given their track record, the solutions they find might again prove useful to society as well. Because at Nikhef, opening up the secrets of the immeasurably huge cosmos and discovering the smallest particles known to man, tend to also lead to promising new breakthroughs at the regular scale of human society.

04

RE SEARCH PRO GRAMMES

The research programmes consist of 10 programme lines, which are described in more details in the Appendix. In this section we provide per programme a short description of the main research goals and the highlights in the past period.

ATLAS

Research Goals

The goal of the ATLAS programme is to solve one or more of the outstanding big picture questions about nature, like: What is the origin of mass of fundamental particles? Are there undiscovered symmetries (and associated fundamental particles)? Do all forces become one? What is dark matter? An important clue to the first question was already discovered by ATLAS in 2012: the Higgs boson. The other questions are still wide open, and answering these questions form the principal scientific challenge for ATLAS in the next decade.

Highlights

- → The highlight of the past five years has been without doubt the discovery of the Higgs boson and the subsequent exploration of the Higgs sector of nature. The Higgs boson plays a pivotal role in the structure of the current best theory of nature – the Standard Model – but was never before observed despite a decades-long effort. Observation of the Higgs boson at the LHC now allows to directly test a great number of fundamental assumptions on the origin of particle mass and on the structure of fundamental forces that were previously inaccessible.
- → Another important goal of the ATLAS programme is to probe the existence of other new fundamental particles or deviating properties of known particles that are associated with proposed theoretical extensions of the Standard Model. The unprecedented collision energy of the LHC in both its first and second run, as well as its larger than expected data volume have resulted in impressive progress on the searches for new phenomena and the much-improved limits on their potential properties. Our contributions have been to the direct searches for strongly produced supersymmetry, properties of top quark pair production and the search for lepton flavour violation.

LHCB

Research Goals

The LHCb experiment revolves around a central research topic that is generally called the flavour problem. Why are there three generations of particles and what is the precise nature of flavour-changing interactions? Why is our universe dominated by matter with respect to antimatter? To investigate these puzzles, LHCb performs precision studies of the interactions of quarks to identify sources of CP asymmetries in nature as well as to probe the quark interactions to highest energy scales. The main laboratory for these precision measurements is the decay of beauty and charm hadrons, allowing the search for subtle quantum fluctuations as a signal for new particles or forces.

Highlights

- The LHCb experiment has made several discoveries on fundamental matter – antimatter asymmetries (CP violation) in processes that involve interactions between quarks. After the phenomenon of CP violation had been found to exist in decays of Kaons (1964) and B_d^0-mesons (2000), LHCb discovered it in decays of B_s^0-mesons, and perhaps even more spectacularly, also recently with B-baryons; particles with similar quark content as protons and neutrons. Since the start of the LHC many manifestations of CP violation have already been observed and the theory parameters describing them, the CKM parameters, are being determined with world leading and ever increasing precision.
- Rare processes of B-meson decays involving the transition of a b-quark to an s-quark have caused excitement in the community. First, LHCb has discovered the existence of the very rare decay process decay $B_s^0 \rightarrow \mu^+\mu^-$, a process that almost cannot occur with known interactions. In addition, other $b \rightarrow s$ transition processes are only consistent with the Standard Model at the level of 4 standard deviations.
- Recently, so-called semileptonic processes in which B-mesons decay into D or K meson particles together with two leptons, seem to indicate the fundamental laws of nature are not identical for the different lepton generations: electron, muon and tau. This phenomenon is called lepton non-universality and, if confirmed, would be a spectacular result that might hint at the reason why there exists three generations of particles.

- For the very first time in charm physics flavour mixing in D-mesons has been observed and CP violating D-decay parameters have been measured with high precision. In QCD spectroscopy new resonances have been discovered that are candidates of either tetra- or penta-quark states of matter. In the area of electroweak physics a precision measurement was performed of A_{FB}, the forward-backward asymmetry of di-muons, resulting in a measurement of weak mixing parameter $\sin^2\theta_w$, to help resolve the puzzle of the long standing discrepancy between LEP at CERN and SLD at SLAC. Searches for heavy long-lived particles have resulted in exclusion limits for hidden valley particles as well as for heavy neutrino states.

ALICE

Research Goals

The main goal of the research is to improve our understanding of Quantum Chromodynamics (QCD), the theory of the strong force, which is part of the Standard Model of Particle Physics. We want to make major contributions to the understanding of the interactions and structure of matter which permeated the early universe and which, we believe, can be recreated and studied at the highest energy particle colliders such as the LHC at CERN.

Highlights

- Successful operation of the current silicon inner tracking detector of the ALICE experiment, in particular the two outer layers for which our institute had a leading contribution in the development and operation.
- Main authorships by Nikhef-scientists of the first and most cited paper in heavy-ion collisions of the ALICE collaboration on the topic of elliptic flow.
- A leading role in the upgrade of the ALICE silicon inner tracking detector.

NEUTRINO TELESCOPES: ANTARES/KM3NET

Research Goals

The main goals of this programme are twofold: to identify and study the sources of high energy neutrinos in the nature and to make a timely determination of the neutrino mass hierarchy.

Highlights

- → Our group conducted the main ANTARES analyses, including the world's first point source search that uses all neutrino types, i.e., electron- muon- and tau-neutrinos.
- → In 2013, the Dutch design was adopted as the baseline design for the KM3NeT neutrino telescope. Compared to earlier solutions, the design represents a large cost saving, allowing for increased science potential.
- → The technology validation programme was successfully completed, including the deployment of a prototype string and tests of the deployment procedure with the NIOZ vessel Pelagia.
- → In 2016, the first full length KM3NeT detector lines were deployed and data taking commenced. As of writing, the first line has been operational for 15 months.
- → KM3NeT has been included on the 2016 ESRFI roadmap of large scale infrastructures.

GRAVITATIONAL WAVES

Research Goals

The primary objective is the direct detection of gravitational waves with the ground-based LIGO and VIRGO interferometers. Detectors capable of observing binary black hole and neutron star mergers have an enormous impact in several key scientific areas. Moreover, these gravitational wave observations are firmly embedded in the wider field of fundamental physics, astronomy, astrophysics and cosmology. Enhancing detection performance with Einstein Telescope and LISA will make it possible to continuously observe the distant, dark, dense and catastrophic nature.

Highlights

- The first direct detection of gravitational waves (GW) with LIGO happened on 14 September 2015, and was named accordingly GW150914. The event was identified as extremely promising already on the day itself, and shortly afterwards its significance was established to be > 5.1σ. Follow-up analyses revealed that it had most likely resulted from the merger of two black holes of 36 and 29 solar masses; no less than 3 solar masses worth of energy was emitted in gravitational waves, making this the most powerful event ever observed by mankind. Also at the detectors, it was sufficiently loud to be visible by eye in the raw data. The detection represented several scientific breakthroughs at once: apart from being the first direct GW detection, it provided the first direct evidence of the existence of black holes; it was also the first observation of a binary black hole merger, and it finally gave us access to the genuinely strong-field dynamics of pure spacetime. A second clear detection came on 26 December 2015, called GW151226, involving black holes of 14 and 8 solar masses.
- The upgrade of Virgo to a second generation gravitational wave detector, the Advanced Virgo project, was brought to completion in 2016. The upgrade has involved the majority of the detector subsystems, with Nikhef giving a decisive contribution to many of them.

\ COSMIC RAYS

Research Goals

The most energetic particles observed in our universe are cosmic rays, which have been measured with energies in excess of 10^{20} eV (=100 EeV).
The origins of, and acceleration mechanisms leading to, these ultra-high-energy cosmic rays are yet unknown. These cosmic rays should interact with the cosmic microwave and other cosmic backgrounds producing photons and neutrinos that have never been observed. Ultra-high-energy cosmic rays interact with the atmosphere in hadronic interactions with centre-of-mass

energies exceeding those of human accelerators (i.e. the LHC) by more than an order of magnitude, i.e. in a region where the Standard Model largely remains untested so far.

The goals of this research programme are to detect ultra-high-energy cosmic rays, including photons and neutrinos, with the best measurement of energy, arrival direction, and composition information to search for point sources of ultra-high-energy cosmic rays, understand their acceleration mechanisms, study their interactions with the cosmic background, and the physics at the highest observable particle interaction energy from their collision with atmospheric nuclei.

Highlights

Surface Detector measurements

- → Determination of the mass composition of ultra-high-energy cosmic rays with the Auger Surface Detector

Radio Detection of high-energy cosmic rays

- → Construction, commissioning and exploitation of the Auger Engineering Radio Array, covering 17 km^2
- → Understanding of the lateral density profile of radio frequency radiation from high-energy extensive air showers
- → Absolute energy calibration of radio detection of high-energy cosmic rays
- → Determination of the mass composition of ultra-high-energy cosmic rays with radio detectors

\ DARK MATTER

Research Goals

The main research goal of the Dark Matter group is to discover, and characterize, the particle responsible for the dark matter observed in the nature. We pursue our research goals through the design, operation and analysis of ultra-sensitive low-background experiments using liquid xenon targets at INFN's Laboratori Nazionali del Gran Sasso (LNGS) underground laboratory in Italy and with R&D work in our local laboratory at Nikhef.

Highlights

- The main highlight of the Nikhef Dark Matter group over the past years is the completion of the XENON1T dark matter experiment and the start of its scientific exploitation in Fall 2016. XENON1T will be the world's most sensitive direct detection dark matter experiment until the start of the next-generation dark matter experiments in 2020. The experiment has two orders of magnitude better sensitivity than XENON100, its predecessor, with a real possibility of discovering the dark matter particle.
- While our group was building XENON1T, we were also part of the XENON100 analysis team, participated in the DARWIN design study and we designed and constructed a xenon R&D setup at Nikhef.

THEORY

Research Goals

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

Highlights

- The theory group has been extraordinarily successful in obtaining external funding, being awarded many grants for both senior staff, and junior scientists. This has led it to grow to well over 40 members in Amsterdam alone, producing over 60 papers in 2016.
- Joining of theorists from Nijmegen working on quantum gravity, and of the Van Swinderen Institute. This further strengthened the central role that the theory group plays in Dutch theoretical particle physics landscape, for instance through the monthly Theory Center meetings.

- Important research results were obtained, such as the calculation of the N3LO Higgs production cross section, the development of new observables and methods in B-physics and QCD, and many results in cosmology, dark matter, gravity and string theory.
- FORM version 4 was published, including major new functionalities, enabling calculations to one loop order more than hitherto.

DETECTOR R&D

Research Goals

Answering the biggest mysteries in physics requires pioneering experiments. New instrumentation ideas need to be initiated and developed long before they can be implemented in Nikhef's scientific experiment: from proof of principle to scientific instrumentation, applying latest technologies, and with an open mind towards industrial applications.

Dynamics of the Detector R&D program:

- Basic instrumentation R&D with (future) Nikhef experimental programmes
- Explore new technologies in synergy with Nikhef engineering departments
- Knowledge transfer with high-tech research institutes, Dutch top-sector & industry

Highlights

- We presented the most precise gaseous pixel detector to date for measuring the position of individual ionisation electrons at the IEEE-NSS 2014 conference. This leads to improved angular (2.5 degrees) and position (in-plane 10 μm) resolutions on fitted tracks. It finds applications in self-triggering and on-chip pattern recognition for use in, e.g., the ATLAS L1 trigger or Proton Radiography.
- Together with the Nikhef Dark Matter group, we constructed XAMS – a xenon facility in Amsterdam– now operational to

investigate detector technologies and xenon medium properties in a dual-phase xenon time projection chamber (TPC).

- Working together with the Nikhef Gravitational Physics group led to alignment and monitoring systems for VIRGO's optical test masses, a programme to develop ultra- sensitive accelerometers for future Gravitational Wave detectors.
- Hosting of the TIPP 2014 conference: *the* Technology and Instrumentation in Particle Physics 2014 (www.tipp2014.nl) conference was held in *De Beurs van Berlage*, downtown Amsterdam from June 2–6 2014. This is a new series of cross-disciplinary conferences on detector and instrumentation falling under the auspices of the International Union of Pure and Applied Physics (IUPAP). It had 450 attendees and brought together world experts from the scientific and industrial communities to discuss current work and to initiate partnerships that may lead to transformational new technologies.
- The awarding of grants like ERC grant to H. van der Graaf in 2012 was very important for the DR&D group and allowed us to start a new field of instrumentation research.

PHYSICS DATA PROCESSING (ADVANCED COMPUTING FOR RESEARCH)

Research Goals

The high-energy physics research effort requires very-large-scale computing infrastructures to accomplish its research goals. Other branches of science are increasingly joining the large-infrastructure club as their research data grows in volume. The PDP group carries out research targeted at solving the computing challenges presented by our local research, research carried out within our national and international collaborations, and when appropriate, by our scientific counterparts in other research domains. Carrying out such research entails actually doing it; experience here and elsewhere shows that reasoning and intuition seldom anticipate all the major hurdles encountered when making significant advances in ICT research infrastructures.
This aspect distinguishes the research at Nikhef from academic research on distributed computing being done in a university setting.

Highlights

- successful application of process algebra to modelling distributed systems
- R & D into manycore applications, results applied to local research and for global LHC infrastructure
- prototype caching proxy storage developed (collaboration with TUE)
- Conference “Computing in High-Energy Physics” (CHEP), premier conference in our field, held in Amsterdam.
- major upgrades to internal and external networking infrastructure
- major upgrade to local high-throughput storage facility

05 EXTERNAL DEVELOPMENTS AND SWOT ANALYSIS

Two national policy developments have influenced and will influence the context in which Nikhef has operated and will operate in the coming period: the Topsector policy and the National Research Agenda (Nationale Wetenschapsagenda or NWA).

TOPSECTOR POLICY

Starting around 2011 the Dutch government launched a policy, in which a large fraction of the budgets from the Netherlands Organisation for Scientific Research (NWO) had to be coupled to programmes in collaboration with industrial and societal activities, divided over nine so called top sectors: areas of economic importance for the Netherlands.

While initially this initiative seemed to be quite a threat to the funding of fundamental research, in practice this policy has worked out reasonably well for Nikhef. One of the defined top sectors is called *High tech systems and materials* (HTSM). In this *Topsector* a dedicated Roadmap has been developed called *Advanced Instrumentation*, in which Nikhef's activities with regard to detector R&D and Advanced Computing, including the associated technical and engineering efforts, have been given a natural place. This has opened up explicit opportunities for cooperation with industry (public private partnerships). In recent years NWO has even provided a dedicated budget increase for this policy. The increase within Nikhef of collaborative projects with industry in the 2011-2016 time frame is partially due to this policy.

DUTCH NATIONAL RESEARCH AGENDA (NWA)

In 2015, the Dutch government asked the 'kenniscoalitie', a broad coalition between universities (VSNU), graduate schools (VH), medical centers (NFU), Royal Academy of Sciences (KNAW), NWO, Employers organizations (VNO-NCW) and Dutch industry (including SMEs) to prepare a National Research Agenda (NWA).

This initiative resulted in a public consultation in which all citizens could pose their most favourite and relevant question on any topic of their liking. In 2016, the almost 12,000 collected questions for the *'Nationale Wetenschaps Agenda'* led to 140 cluster questions. Browsing through these questions led to the identification of 25 'routes' or themes, covering all ranges of questions. Two of these routes particularly deal with curiosity-driven fundamental science. These are Route 4, with the title 'Origin of life on Earth and in the Universe' and Route 5 with title 'Building blocks of matter and Fundaments of Space and Time'. Route 5, organised by Stan Bentvelsen, fits the science portfolio of Nikhef very well and brings particle physics, astronomy, astro(particle) physics, theoretical physics, cosmology, mathematics, chemistry, philosophy together with industry. After consultation of the whole community, this route has defined game-changers; one of which is the Einstein Telescope as the next generation gravitational wave interferometer, possibly to be built in the Netherlands. In 2017 seed money for starting the realisation of some routes has been provided.

The ambition of the NWA is big as it aims for a serious and sustained increase (1 B€) in funding for science and innovation. The NWA has already penetrated the current funding scheme as many proposals are requested to indicate their relevance with respect to this agenda.

SWOT ANALYSIS

The following SWOT analysis shows the current status and context of the Nikhef partnership. While some of the actions listed in response to the weaknesses, opportunities and threats are a continued effort from the current strategy period, most address issues that are part of the strategy for the next period (2017 - 2022), which is summarized in chapter 6.

TABLE 20 **SWOT analysis**

Strengths
Coordination of Dutch efforts in particle physics.
Proven initiative and leadership in highly competitive field.
Highly motivated and experienced technical personnel.
Excellent infrastructure able to accommodate design and construction of large and complex detectors.
Strong and balanced physics portfolio in LHC experiments.
Crucial technical and physics contributions in leading astroparticle physics experiments.
Excellent breeding ground for development of innovative new technologies.
Excellent publication and citation record.
Large impact in outreach and education.
Excellent computing infrastructure, well-connected to experimental collaborations.

Weaknesses	Action
The scientific programmes at Nikhef are not exploiting potential synergies.	Stimulate thematic cross-programme activities.
Nikhef staff shows a significant gender imbalance.	Active participation in gender programmes; scout female talent.
Large collaborations make it difficult for young people to stand out.	Raising awareness at collaborations
Nikhef might not be able to keep attracting enough master students	Improve attractiveness of experimental subatomic physics at bachelor's level
Nikhef building starts to be outdated and showing deficiencies.	Renovation plan

CONTINUE →

Opportunities	Action
The general interest of public in fundamental science is strong.	NWA (National Science Agenda) may lead to funding increment.
Discovery of the Higgs boson allows further understanding of fundamental physics in the very early universe.	Exploit the LHC luminosity upgrades.
The Nikhef design and technology is well visible in the ambitious upgrade plans of the LHC experiments.	Stimulate close involvement of technical departments.
Determination of neutrino mass hierarchy and neutrino astrophysics.	Develop KM3NeT phase-2
First direct observation of gravitational waves opens a new field in astrophysics.	Increase sensitivity of Advanced Virgo
Significant interest in hosting the Einstein Telescope in the Netherlands.	Gather further support to get it built in the Netherlands.
The new eEDM program: a challenging and high-impact in-house experiment	NWO-physics programme has started
The new funding scheme of NWO has shifted part of Nikhef's programmatic funding to the mission budget.	More flexible improvements possible between programmes
Nikhef offers a wide range of valorisation potential in TopSectoren	Enhance links to high-tech industry
SRON and ASTRON in the NWO-I family	Stimulate cooperation.

Threats	Action
Significant uncertainties related to the new funding scheme of NWO.	Make funding agencies aware of the needs for programmatic funding beyond the mission budget.
Funding cycles are short with respect to typical experimental time scales.	Make funding agencies aware of long-term strategy needed for big science.
Delays in the start of new large international projects, such as an e+e- collider	Participate strongly in European particle physics strategy discussion
Funding of KM3NeT phase 2 is not yet secured	Funding proposals submitted.
Insufficient recognition from collaborations for computing efforts.	Keep pressing the need for compensation within collaborations

06

STRA TEGY

The Large Hadron Collider (LHC) at CERN delivers record luminosities, leading to a torrent of scientific results. With the Higgs particle in hand, nature will be unveiled by LHC with unprecedented potency. This journey continues with deeper understanding of the standard Model and the excitement of knowing that new, unknown physics must lie beyond the corner of our current knowledge, ready to be discovered.

Astroparticle physics delivers equally relevant results. In the disclosure of the fundamental laws of the nature, gravitational waves provide a new way to observe the universe. Nikhef is deeply involved in gravitational waves and has strong ambitions in this field for the next decades. Further, Nikhef is making crucial contributions to a new way of detecting neutrinos in the deep Mediterranean Sea by designing and constructing the KM3NeT detector. The 'harvesting' of data further continues with the continuation of Dark Matter research with the XENON1T/nT detector and ultrahigh-energy cosmic rays with the Pierre Auger Observatory in Argentina.

For the near future, Nikhef actively participates in large upgrade plans at the LHC experiments and the continuation in the construction of the astroparticle physics (APP) projects. For the interpretation of the data, theory phenomenology will closely collaborate with the experimental analysis efforts. For a coherent approach to the science drivers the analyses topics may cross individual programme lines.

The physics results that will be obtained during the coming years are crucial for the long-term future of international particle physics and Nikhef. The optimal strategy for the next generation of worldwide accelerators and particularly at CERN will be determined during the coming period. Naturally, the outcome of the international discussions, in which Nikhef actively participates, influences the Nikhef strategy itself. In addition, there are a number of science opportunities that Nikhef plans to investigate in the APP domain. For example, the research of gravitational waves has the potential to become a large fraction of Nikhef activities, in the case that the next generation interferometer Einstein Telescope will be hosted by the Netherlands.

The summary of the Nikhef strategy for the coming years 2017-2022 contains the pillars “proven approaches”, “new opportunities” and “beyond scientific goals” as follows:

01 Proven approaches

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

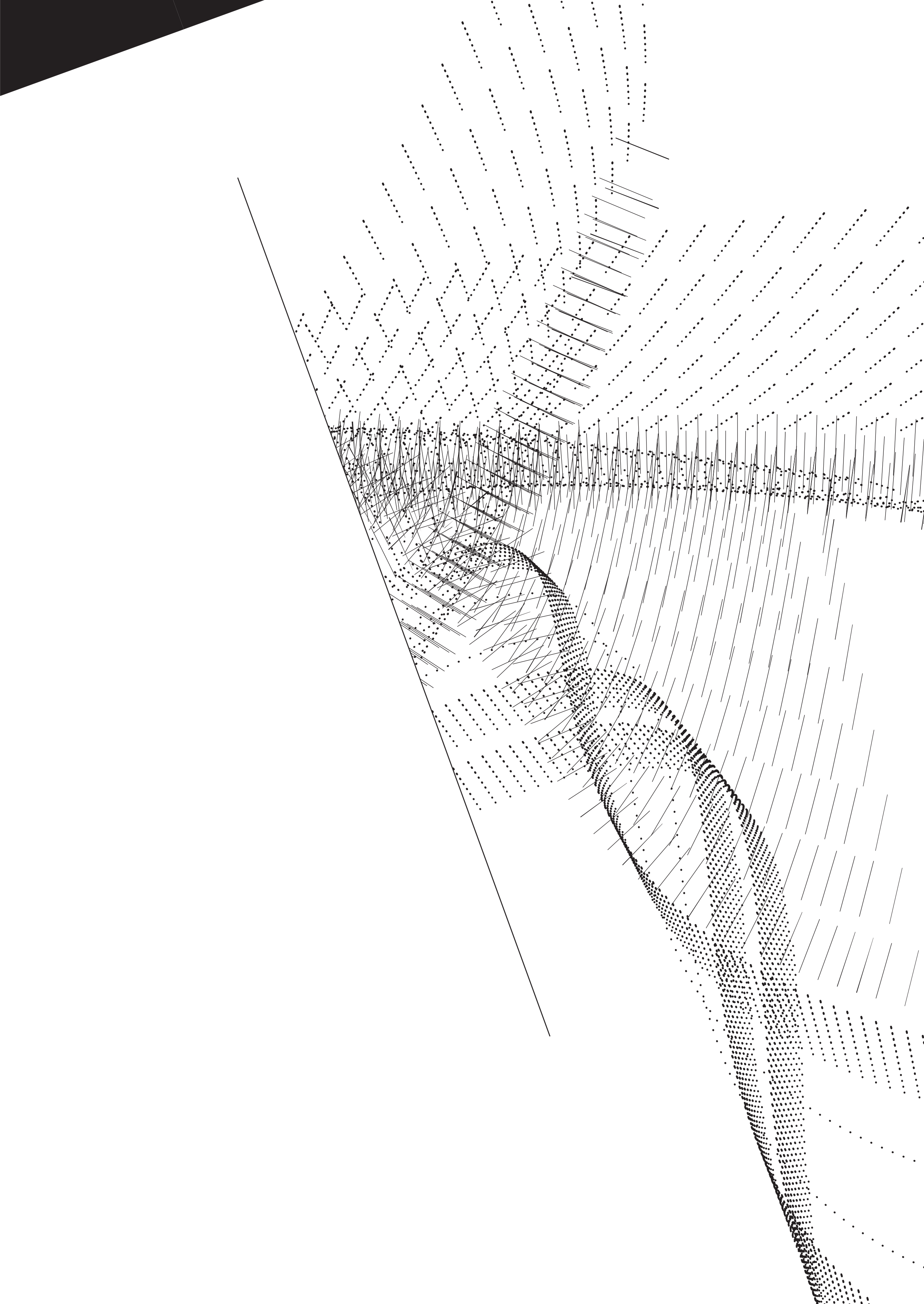
02 New opportunities

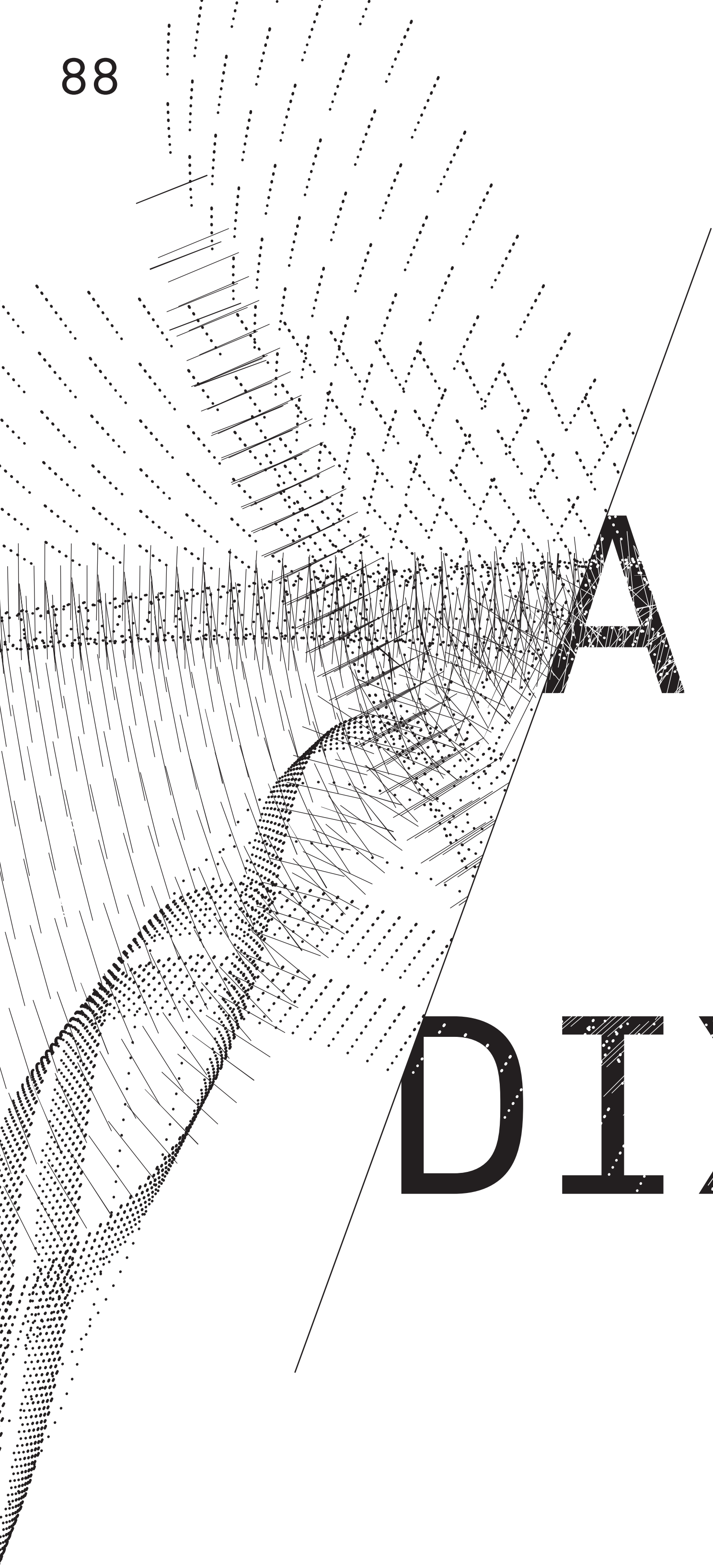
- → Determine the electron electric dipole moment with world-class precision
- → Prepare for a new era of high-energy accelerators
- → Strengthen and exploit the thematic connections between individual scientific programmes
- → Prepare a bid to host the Einstein Telescope in the Netherlands

03 Beyond scientific goals

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

Details can be found in the *Nikhef strategic plan 2017-2022 and beyond.*





APPENDIX

\ RESEARCH PROGRAMMES

ATLAS

Programme organization

Programme leadership:

- → prof. dr. S. Bentvelsen, with two deputies: prof. dr. P. de Jong and prof. dr. N. de Groot until 2013;
- → From 2013 on there have been co-programme leaders: prof. dr. P. de Jong (until 11/14) / prof. dr. W. Verkerke (from 11/14), and prof. dr. N. de Groot.

University partners:

- → UvA, RU

Research Goals

The goal of the ATLAS programme is to solve one or more of the outstanding big picture questions about nature, like: *What is the origin of mass of fundamental particles? Are there undiscovered symmetries (and associated fundamental particles)? Do all forces become one? What is dark matter?* An important clue to the first question was already discovered by ATLAS in 2012: the Higgs boson. The other questions are still wide open, and answering these questions form the principal scientific challenge for ATLAS in the next decade

Searches for new particles

The clearest signature of new physics is the discovery of a new fundamental particle that is produced on-shell. Such a discovery is the holy grail of experimental physics because it is unambiguous and gives immediate information towards the underlying physics. However, unlike the SM guidance for the Higgs boson, there is no narrow guidance on the topology and cross-section of such a signature. Instead, a multitude of theories predict a wide range of signatures. The opportunity for discovery is wide and large, but also diffuse and may not be immediate. The present experimental and theory effort focus on relatively easy large-cross-section signatures that are in discovery reach with O(100) fb-1 of data. Examples of such bottom-up theories include supersymmetry scenarios that favour strong production mechanisms, but also generic Dark Matter models, and extended Higgs sector models. These searches are expected to remain competitive (i.e., not dominated by systematics) until about 2020. As the data sample increases, new lower-cross-section signatures will come within reach, e.g., electro- weak SUSY production, and a reassessment of theories worth pursuing further will need to happen periodically. Saturated searches for which year-2020 limits effectively preclude discovery at the HL-LHC will obviously be dropped. Theoretical guidance on ultra low cross-section new physics that only become of interest in the very long term is still much a work in progress. Recent studies show that the least fine-tuned SUSY scenarios that are compatible with all (astro)physical observations, may preferably result in signatures that are rare and difficult to reconstruct and may only be discovered in ATLAS beyond 2025. Theoretical and experimental progress in the next years will shed more light on the viable range of searches beyond 2020. Notably, a wide range of exotic detector signatures exist, such as long-lived particles and R-parity conserving supersymmetry that offer a complementary window to new physics and have not yet been widely studied.

Precision measurements: exploring the Higgs sector and more

New physics may also manifest itself through modified properties and interactions of known particles: fundamental particles might turn out to be composites, new massive particles could contribute to loop processes, all affecting properties and interactions of known particles. The Higgs boson provides the most fertile hunting ground for such studies as it is both the least tested and the most interesting sector of the SM. Open questions are: is the Higgs fundamental or composite? If fundamental, is it minimal or extended (2HDM, EWS…)? Are Yukawa couplings responsible for the masses of all generations? Is the potential really φ^4? Is the Higgs boson a portal to new Physics? At present only the couplings to W, Z and 3rd generation fermions are established, albeit with 10-20% precision. Many more Higgs couplings are measurable thanks to an unexpected recent gift of nature: a low Higgs mass. The theoretical and experimental frameworks for Higgs precision measurements are consequently still very much a work in progress: at present only Higgs rates are measured assuming SM kinematics. The goal of future precision measurements is to increase the reach in the scale Λ at which new physics occurs in the Higgs sector (1% coupling uncertainty corresponds roughly to probing Λ = 2.5 TeV). By 2020 observation of $H\to\mu\mu$ will provide a first probe of the Higgs coupling to the 2nd generation, and observation of ttH production will provide the first non-loop probe of the Higgs-top coupling. Between now and 2025 all Higgs coupling measurement wills continually improve; no channel is predicted to be strongly systematics dominated. Sensitivity to new physics will likely significantly outperform current projections as novel and sensitive measurements of high-Q and off-shell Higgs production are so far ignored. Future fits that exploit distributions instead of rates will measure the tensor structure of Higgs couplings that are highly sensitive BSM contributions to the Higgs sector. In the long term (2030) Higgs self-couplings will come into reach. Prospects for this very challenging measurement of ultra-low cross-section di-Higgs production are also improving with new analysis techniques. Finally, the abundant production of top quarks and vector bosons offer already now opportunities to perform high precision measurements of the top quark mass, the structure of the Wtb vertex, as well as novel opportunities to study ultra-rare lepton flavour violation processes in the decay of vector boson and τ leptons.

Research Highlights

The highlight of the past five years has been without doubt the discovery of the Higgs boson and the subsequent exploration of the Higgs sector of nature. The Higgs boson plays a pivotal role in the structure of the current best theory of nature – the Standard Model – but was never before observed despite a decades-long effort. Observation of the Higgs boson at the LHC now allows to direct test a great number of fundamental assumption on the origin of particle mass and on the structure of fundamental forces that were previously inaccessible. Higgs bosons are exceedingly short-lived and thus never observed directly, only their decay products are accessible. We have discovered that nature has a comparatively light Higgs boson with a dozen of different decay signatures, none of which are abundant or easy to reconstruct, which has complicated its discovery. The existence of the Higgs boson was inferred through a combined analysis of three of these modes involving its decay into two photons, two Z bosons or two W bosons.
We have made important contributions to two of these and were the lead developer of the combined analysis framework. In the exceedingly rare ZZ decay mode we optimized the sensitivity of the analysis substantially, which helped pass the 5σ discovery barrier. In the more abundant, but harder to

identify, WW mode we were one of the leading institutes in the overall analysis effort. The upside of a light Higgs boson with many decay signatures is that it gives many experimental handles to verify its properties. With a new boson discovered, its intrinsic properties were consistent with those expected of the Higgs boson in the theory. We contributed to measurements of the quantum numbers spin and parity of the new particle in both the WW and ZZ channels by studying the angular correlations between the decay products. These studies have confirmed that the particle has indeed positive parity and spin-0, as predicted. Measurements of the interaction properties of the Higgs boson, quantified in the coupling strengths of the Higgs boson to each of the other particles in the Standard Model, are the ultimate test of its role in the origin of mass and in the structure of fundamental forces.
For these measurements, the multitude of observable Higgs decay modes due to its low mass provides an unexpectedly rich experimental basis. We have contributed to measurements of the Higgs coupling strength to W and Z bosons building on the discovery efforts in the WW/ZZ modes, and have expanded our scope to measurements of the coupling to the top quark and to the tau lepton in other decay modes. Finally, we have built on our expertise in the discovery combination framework to become one of the lead analysers of the combined analysis of all Higgs decay observations to measure its coupling properties. Already on the LHC Run-1 data, first measurements of couplings to seven Standard Model particles (b,t,μ,W,Z,g,γ) have been realized.

Another important goal of the ATLAS programme is to probe the existence of other new fundamental particles or deviating properties of known particles that are associated with proposed theoretical extensions of the Standard Model. The unprecedented collision energy of the LHC in both its first and second run, as well as its larger than expected data volume have resulted in impressive progress on the searches for new phenomena and the much-improved limits on their potential properties. Our contributions have been to the direct searches for strongly produced supersymmetry, properties of top quark pair production and the search for lepton flavour violation.

Research Activities

D0

Nikhef took part in the D0 experiment at the $\sqrt{s}$= 1.96 GeV proton-antiproton collider at Fermilab near Chicago, USA from 1997 until 2013. The emphasis was the hunt for the Higgs boson, but also a few other topics were studied. In particular, Nikhef has played a major role in b-quark tagging and tau-identification. These have also been applied as a tool for Standard Model physics, such as Z-boson decays to b- and tau-pairs. Nikhef contributed strongly to the early use of GRID computing by D0, in the time that GRID computing was under development for the LHC. The physics highlights of D0, to which also Nikhef contributed, are the discovery of Bs oscillations, the precise measurement of the top quark mass and cross section, the discovery of single top production and the 3-sigma hint of the Higgs boson in its decay channel to b-quarks. With the discovery of the Higgs boson at the LHC, the Tevatron hint has de facto become the best measurement to date of the branching ratio of the Higgs boson to b-quarks. In total 14 PhD theses were successfully defended by Nikhef students on D0 physics, with two in the period 2011-2016. Active participation of Nikhef in D0 ceased in 2013. The D0 effort has provided an excellent preparation of Nikhef physicists for ATLAS allowing a fast ramp up of the ATLAS physics analysis by the Nikhef group.

ATLAS

Nikhef has an ongoing participating in the ATLAS experiment. The emphasis in the early phase of the first run of the LHC (2011-2012) has been on the study of top quark production and direct searches for new fundamental particles related to the theory of supersymmetry and searches for the Higgs boson. The early effort to characterize the production of top quarks, the heaviest elementary particle known to date, have been instrumental in the detailed understanding of the performance of the ATLAS detector and in the commissioning of particle identification and reconstruction algorithms. The Nikhef top physics programme has resulted in a wealth of physics results (5 PhD theses in 2011-2016). With the discovery of the Higgs boson in 2012, emphasis shifted from top physics to Higgs boson physics, starting with a strong contribution to the discovery effort and continuing in a broad programme of Higgs exploration as detailed below, resulting in 9 PhD theses in the period 2011-2016. The programme of searches for new fundamental particles and phenomena related to supersymmetry and lepton flavour violation is continuing at full strength along-side the Higgs physics effort: the increased beam energy of the LHC in Run-2 (2015 and onwards) has recently given these efforts a strong boost in their reach (10 PhD theses in 2011-2016).

Nikhef Contributions

Nikhef has made major contributions to the construction of ATLAS. These include the design, construction and commissioning of the outer layer of large monitored drift tubes (MDT) muon detectors in the barrel. Also, one of the endcaps of the silicon tracking detector (SCT) was assembled at Nikhef.

The main upgrade of ATLAS in Phase-0 has been the installation of the IBL, or insertable B-layer in 2014. To maintain b-tagging capabilities when the inner layer of the current pixel detector becomes affected by the accumulated radiation dose, the current beam-pipe was replaced by a smaller-diameter beam-pipe, with silicon pixel sensors mounted on it. Nikhef has been involved in the design and characterization of the FE-I4 read-out chip, the detector cooling system, and in the alignment and performance studies. The IBL has been operating smoothly since 2015 and has already shown to improve the impact parameter resolution by a factor two.

Other contributions to the hardware for run 2 are the firmware upgrade to the muon read-out drivers allowing for an increased data rate in the detector. We also contributed to the trigger system where we built electronics to include the muon trigger information in a new topology trigger and our design of a much improved trigger for events with missing energy.

Nikhef has continued to play a leading role in a number of areas in the software and data reconstruction and analysis. These are muon reconstruction, identification of jet from b-quarks, the trigger system and statistical tools for data analysis. Nikhef also hosts one (out of nine) ATLAS Tier-1 data processing centers that store, reconstruct and simulate ATLAS data.

National and International Collaborations

Nationally the ATLAS group is composed of researchers from the NWO institute Nikhef, the University of Amsterdam and the Radboud University. We operate as one group. Internationally, the ATLAS experiment is based at CERN. It has about 3000 collaborators from over 175 institutes in 38 countries.

Grants and Awards

- Snellius Medal 2015 – Dutch ATLAS group
- Physica Prize 2013 – F. Linde and S. Bentvelsen
- Radboud Science Award 2013 – F. Filthaut and N. de Groot
- Jan Kluyver Thesis Prize 2011 – A. Doxiadis
- Jan Kluyver Thesis Prize 2015 – S. Gadatsch
- ATLAS Thesis Award 2014 – P. Pani
- NWO VICI grant: 2016 – O. Igonkina
- NWO VIDI grant: 2016 – T. du Prée
- FOM Projectruimte
    - 2011 – P. de Jong
    - 2012 – O. Igonkina
    - 2013 – B. van Eijk and S. Bentvelsen
    - 2013 – P. Ferrari
    - 2013 – F. Filthaut and N. de Groot
    - 2016 – M. Vreeswijk (with E. Laenen)
- NLeSC grant
    - 2015 – W. Verkerke
    - 2015 – S. Caron
- EU TALENT grant: 2011 – N. Hessey
- INFIERI grant: 2012 – N. Hessey

Key publications

1 G.Aad et al. (ATLAS Collaboration), *"Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC"*, Phys.Lett. B716 (2012) 1-29.

2 G.Aad et al. (ATLAS Collaboration), *"Evidence for the spin-0 nature of the Higgs boson using ATLAS data"*, Phys.Lett. B726 (2013) 120-144.

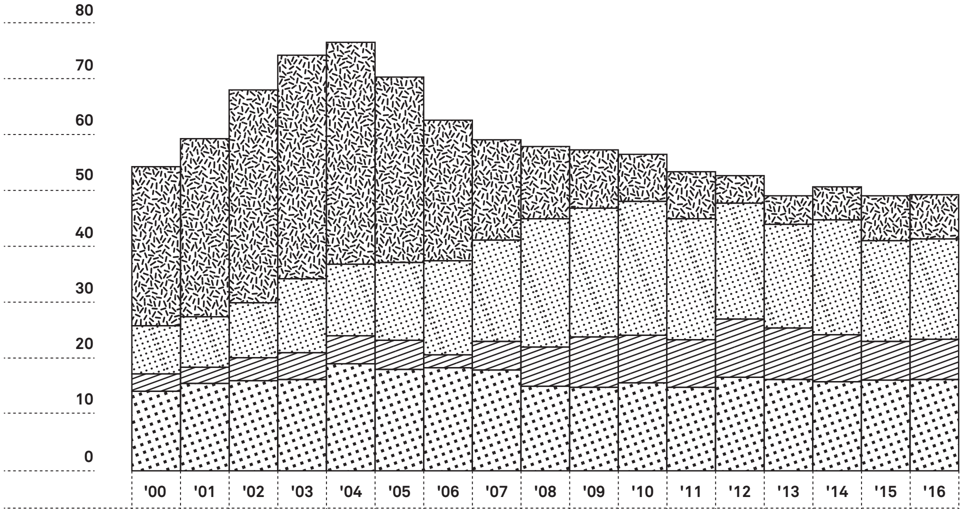
3 G.Aad et al. (ATLAS Collaboration), *"Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s}$=7 and 8 TeV in the ATLAS experiment"*, Eur. Phys.J. C76 (2016) no.1, 6.

4 G.Aad et al. (ATLAS Collaboration), *"Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s}$=8 TeV proton-proton collision data"*, JHEP 1409 (2014) 176.

5 G.Aad et al. (ATLAS Collaboration), *"Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s}$=7 TeV"*, Eur.Phys.J. C71 (2011) 1577.

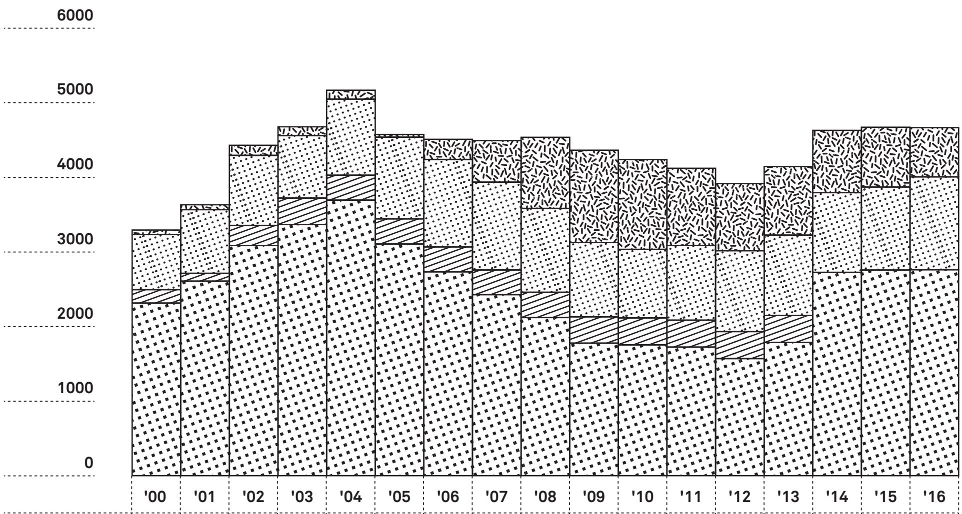
6 G.Aad et al. (ATLAS Collaboration), *"Measurement of the muon reconstruction performance of the ATLAS detector using 2011 and 2012 LHC proton–proton collision data"*, Eur.Phys.J. C74 (2014) no.11, 3130.

FIGURE 09 **Atlas manpower** (in fte)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical staff	28,4	31,8	38	39,9	39,6	33,1	25,1	17,9	12,9	10,4	8,4	8,4	4,9	5,1	5,9	8	7,9
PhD students	8,6	9	9,8	13,2	12,8	13,9	16,8	18,1	22,9	23	23,9	21,6	20,7	18,5	20,5	18	17,9
Postdocs	3,1	2,9	4,1	4,8	5	5,2	2,3	5,1	7	9	8,5	8,5	10,4	9,2	8,4	6,9	7,2
Staff	14,2	15,6	16,1	16,3	19,1	18,1	18,4	18	15,1	14,9	15,7	14,9	16,7	16,3	15,9	16,2	16,3

FIGURE 10 **Atlas budget** (in k€)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects	61	66	135	119	119	36	270	557	953	1.236	1.204	1.034	900	919	835	801	660
Universities	738	853	939	836	1.020	1.095	1.172	1.177	1.124	997	919	1.002	1.084	1.076	1.068	1.113	1.245
FOM-university groups	180	105	270	356	334	337	334	331	339	353	361	361	362	362			
FOM-Nikhef	2.313	2.607	3.084	3.365	3.693	3.105	2.732	2.426	2.119	1.776	1.753	1.723	1.569	1.786	2.725	2.756	2.760

LHCB

Programme Organisation
Programme leader:
→ prof. dr. M.H.M. Merk
Deputy Programme leader:
→ prof. dr. A. Pellegrino
University partners:
→ VU , RUG

Research Goals

The LHCb experiment revolves around a central research topic that is generally called the flavour problem. Why are there three generations of particles and what is the precise nature of flavour-changing interactions? Why is our universe dominated by matter with respect to antimatter? To investigate these puzzles, LHCb performs precision studies of the interactions of quarks to identify sources of CP asymmetries in nature as well as to probe the quark interactions to highest energy scales. The main laboratory for these precision measurements is the decay of beauty and charm hadrons, allowing the search for subtle quantum fluctuations as a signal for new particles or forces.

The activities of the Nikhef group include both analyses of CP-violation and rare decays as well as the construction and operation of tracking detectors (VELO and Outer Tracker) in about equal shares.
The central theme of the group has been tracking detectors and (online) reconstruction of charged particle final states.

Research Highlights

The focus of the LHCb experiment is flavour physics of heavy quarks, with an emphasis on b-quark decays. LHCb has obtained first evidence of the occurrence of new phenomena of CP violation, including time-dependent as well as direct CP violation in B_s^0 decays and CP violation in b-baryons.
In addition to these discoveries, LHCb has published world leading precision measurements of CP violating phenomena including the CKM unitary triangle angles β and γ, and the B_s^0 mixing phase ϕ_s. LHCb performed the world best measurements on both B_d^0 and B_s^0 quark oscillations as well as on the indirect CP violation parameters a_{sl}^d and a_{sl}^s.

Measurements of rare decays have provided a wealth of new experimental results. The very rare decay $B_s^0 \rightarrow \mu^+\mu^-$ has been observed and even the decay $B_d^0 \rightarrow \mu^+\mu^-$ is being scrutinized. The measurements of decays related to the b→s transition have attracted a lot of attention in the community as the consistency with current theoretical calculations is only at the 4σ level. A similar discrepancy is currently observed for semi-leptonic b-decays testing lepton universality.

Furthermore, the collaboration has developed a rich physics programme beyond b-physics. For the very first time in charm physics flavour mixing in D-mesons has been observed and CP violating D-decay parameters have been measured with high precision. In QCD spectroscopy new resonances have been discovered that are candidates of either tetra- or penta-quark states of matter. In the area of electroweak physics a precision measurement was performed of A_{FB}, the forward-backward asymmetry of di-muons, resulting in a measurement of weak mixing parameter $\sin^2\theta_w$, to help resolve the puzzle of the long standing discrepancy between LEP at CERN and SLD at SLAC. Searches for heavy long-lived particles have resulted in exclusion limits for hidden valley particles as well as for heavy neutrino states.

Although the spectrometer had not been designed for heavy ions, the LHCb collaboration includes a growing activity on heavy ion physics at forward rapidities, in particular for p-Pb and non-peripheral Pb-Pb collisions, as well as fixed target runs for various nuclei.

Research Activities

The long-term physics analysis strategy of the Nikhef group includes both precision measurements of CP violation as well as studies of rare decay processes. In addition, during the early phase of data-taking several preparatory measurements were done. A concise summary of the research activities of the Nikhef LHCb group is represented as follows:

- Physics analysis projects:
  - Early data analyses:
    - Charm production cross section,
    - Production ratio of B_s^0 and B_d^0 mesons: f_s/f_d,
    - Decay of charmed beauty: $B_c^+ \rightarrow B_s^0 \pi^+$.

- CP violation studies:
  - Determination of the CKM angle γ,
  - Measurement of the phase of the B_s mixing amplitude,
  - Measurement of the mixing asymmetry parameters a_{sl}^{d} and a_{sl}^{s}.
- Rare decay studies:
  - Measuring the branching ratio of very rare decays,
  - Testing lepton flavour universality,
  - Searching for heavy long-lived particles.

- Detector technology projects:
  - Operation and maintenance of the VELO detector and construction of the pixel detector upgrade,
  - Operation and maintenance of the Outer Tracker and construction of the scintillating fiber upgrade,
  - Evolving developments for the High Level Trigger in Run-1 and Run-2 and design of the High Level Trigger upgrade.

Nikhef Contributions

The investments for the construction of the detectors were:

- LHCb-1: 4.950 M€, corresponding to 9% of the collaboration,
- LHCb-Upgrade: 3.2 M€, corresponding to 7% of the collaboration.

Early-data analyses

After a first paper on the production cross section of open charm particles, the Nikhef group focused on early data results from measurements of branching fractions. To be able to normalize B_s^0 branching fraction ratios with respect to known B_d^0 decay rates, we determined the fragmentation fraction to produce B_s^0 mesons w.r.t. B_d^0 particles, the so-called f_s/f_d ratio, as well as the kinematic dependence of the produced b-quark. This measurement lays the foundation for all further measurements of branching ratios of B_s^0 meson decays. Subsequently, we published a similar ratio for Lambda-b baryon over B^0 meson production. Our group performed branching ratio measurements of fully hadronic $B_s^0 \to D_s \pi$ and $B_s^0 \to D_s K$ processes; the former of which is currently the most precise Bs branching ratio known to date, while the ratio of $B_s^0 \to D_s K$ over $B_s^0 \to D_s \pi$ decays allows to determine the magnitude of V_{ub}. Also, we observed for the first time the decay $B_c \to B_s^0 \pi$ and measured its branching ratio.

CP Violation Measurements

The main CP violation projects of the group are also two of LHCb's key measurements related to CP violation originating from the interference of mixing and decay amplitudes. They are the measurement of the B_s^0 mixing phase ϕ_s with $B_s^0 \to J/\psi\ \phi$ decays, and the measurement angle γ with $B_s^0 \to D_s K$ decays. For both analyses two results have been produced, the first for 2011 data and the second for the whole Run-1 data. Nikhef contributions to the ϕ_s analysis include a measurement of both angular and decay-time dependence, implemented in the so-called P→VV (pseudoscalar to vector-vector) framework. For the time-dependent angle γ analysis, Nikhef group members have contributed to the event selection, efficiency calculations, and decay-time fitting. In both the ϕ_s and the γ analyses the effects of decay time resolution were modelled by Nikhef group members, exploiting our experimental experience of track and vertex reconstruction.

In addition to these key-measurements, Nikhef students published papers on the measurement of CKM mixing phase ϕ_d with $B_d^0 \to J/\psi\ K_s$ decays and a measurement of the equivalent decay $B_s^0 \to J/\psi\ K_s$, which is required to evaluate the penguin contributions, to related the ϕ_d measurement to the CKM angle β. We plan to continue precision measurements with tree decays (angle γ with $B_s^0 \to D_s K$), with box decays (the mixing phase ϕ_s with $B_s^0 \to J/\psi\ K^+K^-$) and with pure penguins decays (e.g. with the $B_s^0 \to \phi\phi$ decay).

A second activity is searching for CP violation purely occurring in the B - Bbar mixing process, which can be accessed with semileptonic B decays. Nikhef contributed first by a precise measurement of the mixing frequency Δms with semileptonic decays, and subsequently by measuring CP violation parameters in both B_d^0 (a_{sl}^d) and B_s^0 (a_{sl}^s) mixing. These measurements triggered attention in the community as they refuted an earlier signal from the D0 collaboration. Finally, we published a paper setting limits of breaking Lorentz symmetry using semileptonic decays and B meson mixing.

Rare decays

The second research line focuses on studies of rare B-meson decays. Most prominent is the measurement of the branching ratio of the very rare decays $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$, where our main responsibilities include the normalization and efficiency determination in the published LHCb papers. A Nikhef postdoc and a PhD student were also involved in the combination of the results of CMS and LHCb leading to the discovery of the $B_s \rightarrow \mu^+\mu^-$ process, published in an article in nature. The project has recently been expanded in our group to include the search for lepton flavour violating decays $B_{(s)} \rightarrow e\, \mu$.

Apart from searches for very rare decays, the Nikhef semileptonic research group has published a test of lepton universality comparing decays of $B \rightarrow D^*\tau\nu$ to $B \rightarrow D^*\mu\nu$, which has attracted a lot of attention, since the world average result of these measurements shows a 4σ discrepancy with the Standard Model expectation. This measurement will soon be complemented by corresponding measurements with the D meson in addition to the D*. Our group also contributed to reconstruction of the decay $B \rightarrow K\, e^+e^-$ to test lepton universality in comparison to $B \rightarrow K\, \mu^+\mu^-$ and finally to the evidence of exotic resonant penta-quark states in $\Lambda_b^0 \rightarrow J/\psi\, p\, \pi^-$ decays.

LHC data taking and Detector Operation

Nikhef invested heavily in the construction of several LHCb sub-detector systems. Contributions include detector mechanics for the Vertex Detector (vacuum technology, CO_2 cooling, detector open-close positioning mechanics, pile-up trigger), as well as all aspects of the Outer Tracker (modules, electronics, infrastructure) and the High Level Trigger. During the LHC run-1 period (2010-2012) and run-2 period (2015-2018), Nikhef held operational responsibilities for their subsystems, the Vertex Detector (VELO), Outer Tracker (OT) and High Level Trigger (HLT). Subsequently to the construction, installation and commissioning of the detector hardware, group members have contributed with track and vertex reconstruction algorithms.

Vertex Detector operation

The Nikhef group tasks in the VELO include the vacuum system, cooling, motion control and PileUp detector operation. The VELO detector vacuum is directly linked to the LHC beam vacuum and to avoid damage to the detector encapsulation, a pressure difference of less than 5 mbar must be maintained at all times, both under vacuum pumping conditions and under atmospheric pressure neon operation during shutdowns. Similarly, to prevent thermal runaway of irradiated detectors the CO_2 cooling system should be operative at all times, including winter-stops. Nikhef has continuously monitored and operated the detector cooling, including regular refurbishment of the system by mechanical engineers. Also, the motion system to position the detectors around the collision point under stable physics conditions is continuously monitored. Nikhef has constructed and operated 4 dedicated modules in the VELO detector as part of the level-0 PileUp triggers. These detector modules have been instrumental in physics with beam-gas collision and for the precision measurement of the LHC luminosity.

Outer Tracker operation

The OT is a large surface drift tube detector constructed largely by Nikhef. Our group carried many responsibilities for OT operation. It includes monitoring of the composition of the drift gas mix quality and calibration of the drift-time behaviour of the straws, maintenance and replacements of electronics modules, tuning timing and t0 calibrations and determining alignments of individual modules. As a result of these calibrations, a detector resolution of better than 200 μm, within the design expectation, was achieved. Two dedicated efforts were invested to continuously monitor the behaviour of the detector under irradiation, since a potentially harmful effect was discovered in dedicated tests in the lab. The first was a campaign to monitor the detector gain, performing dedicated in-situ measurements with a radioactive source during LHC stops. The second was a dedicated tracking algorithm that allows the determination of possible gain variations through a threshold scan performed with special calibration runs during LHC data taking.

High Level Trigger

Together with the CERN group, Nikhef developed the software trigger of LHCb: the High Level Trigger (HLT). For the current High Level Trigger, Nikhef developed the framework and has also contributed with algorithms for track reconstruction. Nikhef is author of the Gaudi::Functional design, which forms the basis for the multithreaded parallel trigger that is foreseen for the upgrade. An ongoing campaign to optimize the algorithms has demonstrated a continuously improved performance of the trigger. This gain in performance allows to carry out real time calibrations and alignments such that off-line quality reconstruction is now available online. The development of the so-called turbo stream, an investment by a Nikhef postdoc, has a growing use in the collaboration and is considered the baseline for the upgrade.

Leadership positions in the collaboration

The prominence of the Nikhef group in the LHCb collaboration can be recognized by the fact that Nikhef is deeply involved in analyses and sub-detector constructions and is reflected in project leadership positions as well as coordination positions:

Project Leaders and coordinators:

- → Project leader Outer Tracker: 2012-2017
- → Deputy Project Leader vertex Detector: 2010-2012
- → Project Leader High Level Trigger: 2012-2014
- → Operations Coordinator: 2010-2013
- → LHCb Run Coordinator: 2017

Physics Coordination (there were eight Working Groups in LHCb) :

- → LHCb Physics Coordinator: 2014-2015
- → Deputy LHCb Physics Coordinator: 2012-2013
- → “QCD, Electroweak, Quarkonia” working group: 2012-2013 and 2015 - 2017
- → “B to charmonia decays” working group: 2013-2014
- → “Semileptonic B decays” working: 2013-2015 and 2017

National and International Collaborations

Collaboration with Theory

There is an ongoing collaboration at Nikhef with colleagues of the flavour physics theory group, under the leadership of R. Fleischer. These collaborations have resulted in nine publications that included new analysis strategies in flavour physics and were related to the analyses done by the experimental group. One student has finished a thesis on a combined theory-experimental research project, while several informal collaborations are ongoing. To have in-house theory expertise is a strong asset for Nikhef.

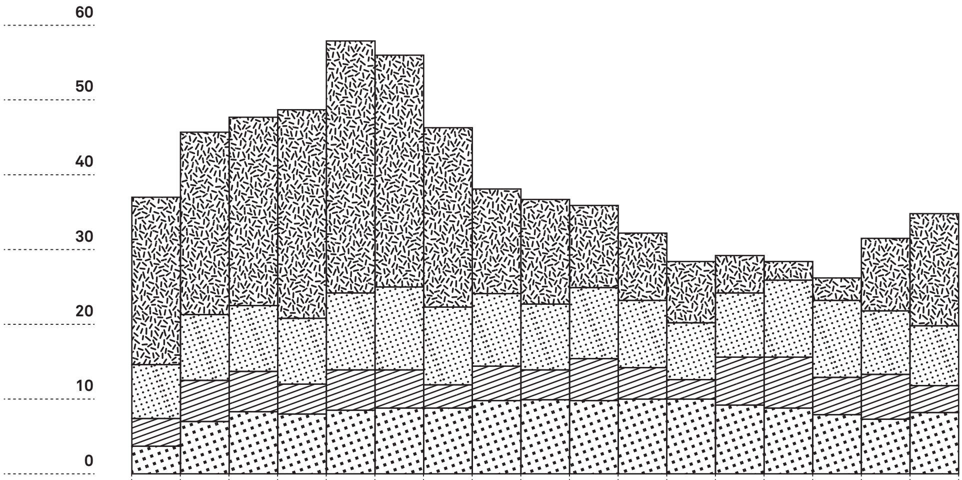
Grants and Awards

- LHCb early career scientist prize: 2016 – S. Benson
- Jan Kluyver Thesis prizes:
  - 2012 – D. van Eijk
  - 2016 – S. Tolk
- NWO VICI Award:
  - 2017 – W. Hulsbergen
  - 2017 – N. Tuning
- NWO VIDI Award:
  - 2014 – J. van Tilburg
- FOM Projectruimte: 2017 – R. Fleischer & M. Merk
- Marie Curie fellowship: 2017 – S. Benson

Key Publications

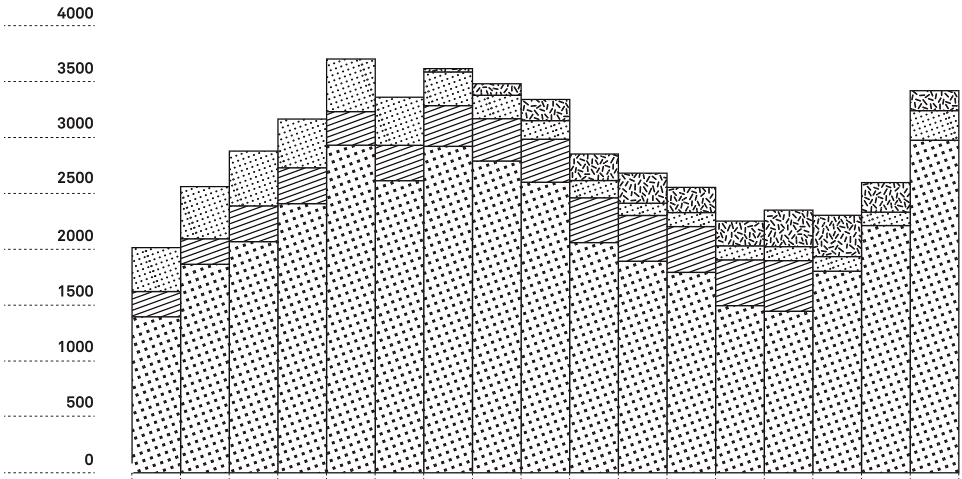
1. K. De Bruyn et al., *“Probing New Physics via the* $B_s \to \mu^+\mu^-$ *effective lifetime”*, Phys. Rev. Lett. 109 (2012) 041801. [219 citations as of Feb 17, 2017].
2. V. Kachatryan et al., (CMS and LHCb Collaborations), *“Observation of the rare* $B_s \to \mu^+\mu^-$ *decay from the combined analysis of CMS and LHCb data”*, Nature 522 (2015) 68. [248 citations as of Feb 17, 2017].
3. Roel Aaij et al., (LHCb Collaboration), *“Measurement of the semileptonic CP asymmetry in B – B-bar mixing”*, Phys.Rev.Lett. 114 (2015) 041601. [54 citations as of Feb 17, 2017].
4. Roel Aaij et al., (LHCb Collaboration), *“Measurement of the ratio of Branching Fractions* $B(B \to D^* \tau \nu)/B(B \to D^* \mu \nu)$*”*, Phys.Rev.Lett. 115 (2015) 159901. [175 citations as of Feb 17, 2017].
5. Roel Aaij et al., (LHCb Collaborations), *“Precision measurement of CP violation in* $B_s \to J/\psi K^+K^-$ *decays”*, Phys.Rev.Lett. 114 (2015) 041801, [89 citations as of Feb 17, 2017].

FIGURE 11 **LHCb manpower** (in fte)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical staff	22,4	24,4	25,2	27,9	33,7	31	24	14	14	11	9	8,2	5	2,5	3	9,7	15
PhD students	7,2	8,8	8,8	8,8	10,3	11,1	10,4	9,7	8,8	9,5	9	7,6	8,6	10,3	10,3	8,5	8
Postdocs	3,7	5,5	5,4	4	5,4	5,1	3,1	4,6	4	5,6	4,2	2,6	6,4	6,8	5	6	3,6
Staff	3,7	7	8,3	8	8,5	8,8	8,8	9,8	9,9	9,8	10	10	9,2	8,8	7,9	7,3	8,2

FIGURE 12 **LHCb budget** (in k€)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects							30	103	190	237	268	225	222	326	369	264	179
Universities	392	467	490	436	470	430	301	210	165	155	110	125	125	125	130	120	263
FOM-university groups	226	227	319	320	299	316	363	377	384	399	408	409	408	452			
FOM-Nikhef	1.392	1.861	2.063	2.402	2.925	2.607	2.914	2.783	2.594	2.055	1.889	1.789	1.492	1.442	1.800	2.207	2.969

ALICE

Programme organization
Programme leader:
- prof. dr. T. Peitzmann (2011-2013), prof. dr. R. Snellings (2013-present)

University partners:
- UU

Research Goals

The main goal of the research is to improve our understanding of Quantum Chromodynamics (QCD), the theory of the strong force, which is part of the Standard Model of Particle Physics. We want to make major contributions to the understanding of the interactions and structure of matter which permeated the early universe and which, we believe, can be recreated and studied at the highest energy particle colliders such as the LHC at CERN.

Research Highlights
- Successful operation of the current silicon inner tracking detector of the ALICE experiment, in particular the two outer layers for which our institute had a leading contribution in the development and operation.
- The main authors of the first and most cited paper in heavy-ion collisions of the ALICE collaboration on the topic of elliptic flow.
- A leading role in the upgrade of the ALICE silicon inner tracking detector.

Research Activities

The research area is experimental heavy-ion physics and our experimental setup, called ALICE (A Large Ion Collider Experiment), is located at LHC.

The main aim of the ALICE collaboration is to study a new state of matter, the Quark-Gluon Plasma (QGP), where quark and gluon degrees of freedom are no longer confined inside hadrons. The QGP is studied using collisions of heavy nuclei, mainly Pb+Pb, with the ALICE detector at the top energy of the LHC. The ALICE experiment has observed the creation of such hot hadronic matter at unprecedented values of temperatures, densities and volume. These measurements surpass, both in precision, kinematic reach and diversity, all prior measurements. The Dutch team, is analysis-wise one of the most productive teams (e.g. the elliptic flow analysis was led by one of us) of the ALICE collaboration. This was e.g. convincingly demonstrated by the large number of Dutch contributions to the main conferences in the field, as well as the substantial number of personnel grants awarded to members of the Dutch ALICE team. The ALICE results have, second to the Higgs publications, also led to the most cited LHC publications (and as a result two Nikhef consortium members made it to the top ten of the most cited scientists in the Netherlands).

Within the broad physics programme of ALICE, the Nikhef group focusses on determining the medium properties of the QGP using: 1) studies of the angular correlations between the particles produced in heavy-ion collisions (R. Snellings, P. Christakoglou), and 2) measurements of the modification of so-called electromagnetic probes (T. Peitzmann) and hard probes, where the latter include jets (M. van Leeuwen) and heavy flavour (A. Mischke, A. Grelli, P. Kuijer). While there is strong overlap between the sub-fields of research, the distribution of the focus of staff members (as indicated above) ensures a well-balanced coverage of these topics.

Perhaps the largest scientific challenge in heavy-ion physics is that it deals with non-perturbative strong-interaction phenomena so that observations usually cannot be confronted with *ab initio* calculations based on first principles. Instead, a wide variety of models are used to relate the measurements to the emergent complex properties of the medium created in the collisions. This makes heavy-ion physics a very challenging, but rich, field incorporating aspects of different areas of physics such as perturbative QCD, lattice QCD, particle physics, nuclear physics, the AdS/CFT correspondence, thermodynamics and relativistic hydrodynamics. For these different topics we also collaborate with theorist, often in-house.

Nikhef Contributions

Our group has been instrumental in several of the main achievements in the experimental studies of the Quark-Gluon Plasma, both at the Brookhaven relativistic heavy ion collider (RHIC), and at the LHC at CERN. From the many observables that probe the properties of the QGP, the measurement of anisotropic flow probably has had the highest impact in the last decade. It led to the finding at RHIC that the medium created in ultra-relativistic heavy-ion collisions behaves – unexpectedly – as an almost perfect liquid instead of a weakly interacting gas of quarks and gluons. Our group played an important role in this discovery, which has generated considerable interest, also from the general public. The first heavy-ion flow paper from the LHC in 2010 by ALICE confirmed the perfect liquid also at much higher collision energies. Our group played the leading role in the anisotropic flow analysis of ALICE. In particular, we, in large part, developed and implemented the sophisticated statistical techniques that are needed for a reliable measurement of anisotropic flow in ALICE. This development led to many highly visible and cited papers.

Other important signals of the QGP, the so-called hard probes, are very abundant at the LHC and have only there become truly effective. This concerns the energy loss of partons in the produced medium used to constrain its density, and more specifically the behaviour of heavy quarks, such as charm and beauty. In addition, the electromagnetic radiation spectrum can yield information on the early temperature of the hot matter. We contributed significantly to the first ALICE publication on parton energy loss of charged particles and to the first measurement of the suppression of D-mesons as well as the elliptic flow of particles containing charm quarks.

Our group members have had leading positions in many physics- as well as detector hardware topics in ALICE, e.g., Physics Working Group Convenors (now R. Snellings, T. Peitzmann, previously also M. van Leeuwen and P. Christakoglou) as well as Physics Analysis Group Convenors, Upgrade Coordinator (T. Peitzmann 2011-2013), Project Leader of the Outer Layers of the Inner Tracking System Upgrade (P. Kuijer), Management Board Members (T. Peitzmann) and Deputy Physics Coordinator (M. van Leeuwen) as well as Physics Coordinator (M. van Leeuwen, from 2017).

National and International Collaborations

The ALICE collaboration was established in 1992 and the Nikhef group joined in 1994. Currently ALICE consists of about 1,800 physicists (including about 300 PhD students), engineers and technicians from 174 institutes in 41 countries around the world. The Dutch ALICE group belongs to the 10 largest groups within ALICE. We participate and collaborate with the Institute for

Theoretical Physics (ITP) at Utrecht University and with the Nikhef theory group. Examples are work with dr. U. Gursoy (ITP) and prof. dr. E. Laenen (Nikhef and ITP), as well as with prof. dr. G. Arutyunov (ITP) in the past. We collaborate with the ITP by having joint bachelor and master students, and several examples exist of successful joint proposals for PhD students. In addition, we also collaborate currently with CERN and more universities in different countries for joint PhD positions.

Grants and Awards

- → NWO VENI Award: 2012 - A. Grelli
- → NWO VIDI Award: 2014 - A. Grelli
- → NWO VICI Award:
  - → 2016 - A. Mischke
  - → 2012 - R. Snellings
- → FOM Projectruimte:
  - → 2013 - A. Mischke
  - → 2015 - T. Peitzmann
- → ERC Proof of Concept: 2014 - A. Mischke
- → COST Grant: 2013 - A. Mischke
- → ALICE PhD thesis award: 2015 - D. Thomas
- → Top ten most cited scientists in the Netherlands: 2012 - T. Peitzmann & R. Snellings

Key Publications

1 J. Adam et al. (ALICE Collaboration), *"Direct photon production in Pb-Pb collisions √s(NN)=2.76 TeV"*, Phys. Lett. B 754 (2016) 235-248.

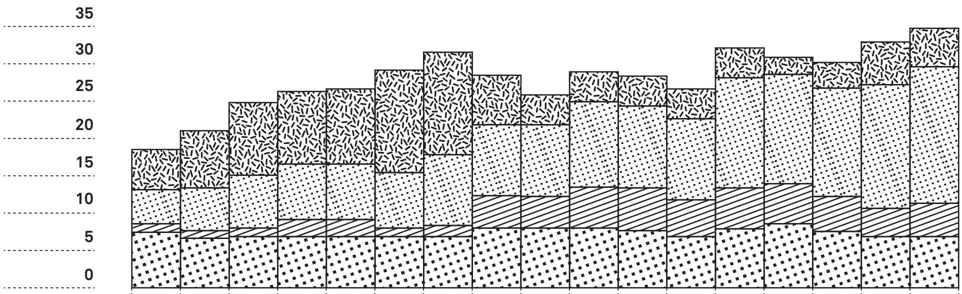
2 K. Aamodt et al. (ALICE Collaboration), *"Suppression of charged particle production at large transverse momentum in central Pb-Pb collisions at √s(NN)=2.76 TeV"*, Phys. Lett. B 696 (2011) 30-39.

3 K. Aamodt et al. (ALICE Collaboration), *"Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV"*, Phys. Rev. Lett. 105 (2010) 252302.

4 K. Aamodt et al. (ALICE Collaboration), *"Higher harmonics anisotropic flow measurements of charged particles in Pb-Pb collisions at 2.76 TeV "*, Phys. Rev. Lett. (2011) 107 032301.

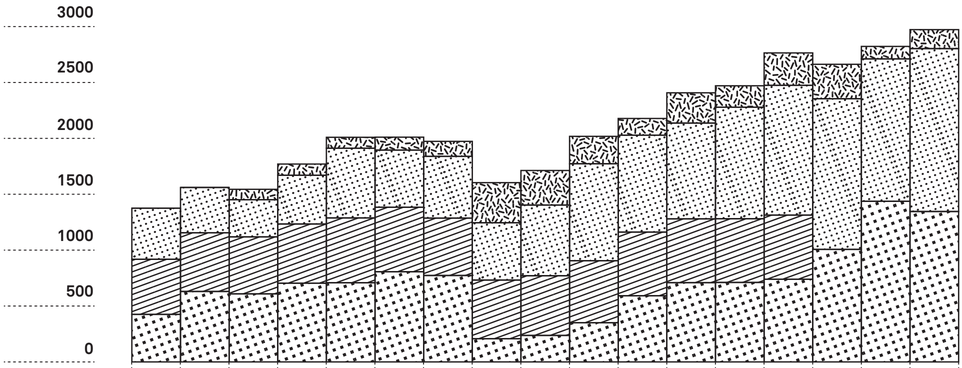
5 B. Abelev et al. (ALICE Collaboration), *"Measurement of charm production at central rapidity in proton-proton collisions at √s = 7 TeV"*, J. High Energy Phys. 01 (2012) 128.

FIGURE 13 **Alice manpower** (in fte)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical staff	4,7	6,7	8,5	8,5	8,8	12	12	5,8	3,5	3,5	3,5	3,5	3,5	2	3	5	4,5
PhD students	4	5	6,2	6,5	6,5	6,5	8,3	8,3	8,4	10	9,6	9,5	12,9	12,8	12,7	14,5	16
Postdocs	1	0,9	1	2	2	1	1,3	3,8	3,7	4,8	5	4,3	4,8	4,7	4,1	3,3	3,9
Staff	6,5	5,8	6	6	6	6	6	7	7	7	6,7	6	6,9	7,5	6,6	6	6

FIGURE 14 **Alice budget** (in k€)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects	0	0	77	83	81	96	112	299	257	204	124	225	159	241	256	93	141
Universities	380	338	277	363	519	425	459	426	526	721	721	713	830	965	1121	1059	1212
FOM-university groups	410	436	424	440	482	480	427	436	444	461	474	474	474	477			
FOM-Nikhef	353	524	506	586	589	671	643	173	197	292	492	590	591	615	837	1195	1119

NEUTRINO TELESCOPES: ANTARES/KM3NET

Programme organization
Programme leader:
→ dr. A. Heijboer
University partners:
→ UvA

Research Goals
The main goals of KM3NeT are twofold:
→ to identify and study the sources of high energy neutrinos in the nature;
→ to make a timely determination of the neutrino mass hierarchy.

Research Highlights
→ Our group conducted the main ANTARES analyses, including the world's first point source search that uses all neutrino types, i.e., electron- muon- and tau-neutrinos.
→ In 2013, the Dutch design was adopted as the baseline design for the KM3NeT neutrino telescope. Compared to earlier solutions, the design represents a large cost saving, allowing for increased science potential.
→ The technology validation programme was successfully completed, including the deployment of a prototype string and tests of the deployment procedure with the NIOZ vessel Pelagia.
→ In 2016, the first full length KM3NeT detector lines were deployed and data taking commenced. As of writing, the first line has been operational for 15 months.
→ KM3NeT has been included on the 2016 ESRFI roadmap of large scale infrastructures.

Research Activities

The Nikhef group has been active in KM3NeT's precursor experiment ANTARES. This experiment successfully demonstrated the proof of principle for a deep-sea neutrino telescope. We have been active in the online filtering of data. Our group has authored the muon-track and electron-shower reconstruction algorithms, which underpin the full physics programme of the project. We have led the searches for point sources that culminated in the most stringent limits for neutrino sources in the southern sky, using -- for the first time -- all neutrino flavours. The first results from ANTARES constraining the neutrino emission associated with Gamma Ray Bursts were achieved by our group. In addition, students have been involved in searches for neutrinos produced by cosmic rays in the Galactic plane.

Building on the experience in ANTARES, members of our group have developed the most accurate, both in angle- and in energy resolution, muon track reconstruction. In addition, an accurate electron-cascade reconstruction algorithm has been written. Both these algorithms offer greatly improved angular resolution compared to the IceCube detector. This positions KM3NeT as the ideal instrument to identify the sources of the cosmic neutrinos that have now been shown to exist by IceCube. The cascade reconstruction offers degree-level resolutions, which allows all neutrino flavours to be used for neutrino astronomy. It also serves as a basis for detecting tau neutrinos by resolving the 'double-bang' signature. A study done in our group shows that this allows to significantly lower the detection threshold for tau neutrinos.

The group has been at the forefront of the data analysis of the deployed KM3NeT detection lines. The data illustrate the power of Nikhef's detector concept with many small photo-multiplier tubes within one optical module, which allows for greatly enhanced background rejection and a better measurement of the intensity of the Cherenkov light. Nikhef students have measured the first muons and validated the efficiency and timing accuracy of the detector.

We were among the initiators of the feasibility study for the neutrino mass hierarchy with KM3NeT/ORCA. After initial efforts by the staff, one of the students in the Nikhef group, secured via an ASPERA grant, now leads this effort in KM3NeT.

Nikhef Contributions

Over the past five years, Nikhef has been a main driving force in the realisation of the KM3NeT project. From 2013 until 2017, M. de Jong was spokesperson of the collaboration; as such, he was the PI of the proposal to include KM3NeT on the ESFRI roadmap, and of a successful H2020 proposal.

At the termination of his Spokesperson term, Nikhef remains involved in the management of KM3NeT with the appointment of E. Koffeman as Technical Coordinator and A. Heijboer as Deputy Spokesperson.

During 2015 and 2016, Nikhef postdoc D. van Eijk was responsible for the international coordination of the optical module production. Within the KM3NeT collaboration, Nikhef engineers G. Kieft and E. Berbee have the responsibility for the mechanics and optical data network.

Nikhef has provided the design of the optical module for KM3NeT where, for the first time in neutrino telescopes, 31 small and inexpensive photo multiplier tubes are used inside a single pressure-resistant glass sphere. These spheres, so-called Multi-PMT optical modules, are connected together by thin synthetic ropes to form a 750 m long string-like detection unit. The design of both the optical module and the detector line is a production of Nikhef's strong mechanical technology department.

The implementation of the optical modules was made possible by several innovations developed at Nikhef. Firstly, the photo multiplier tubes are provided with high voltage through a new and extremely low power Cockroft-Walton circuit that incorporates a direct digitisation of the analogue output signal. The second crucial innovation was the implementation of many sub-nanosecond time-to-digital converters (TDC) within a field programmable gate array (FPGA). The same FPGA is responsible for the communication with the shore station via a high bandwidth fibre-optic network, also designed at Nikhef. KM3NeT is an early adopter of the White Rabbit system, which provides sub-ns timing accuracy. Supported by the European ASTERICS programme, we have provided the implementation of White Rabbit in KM3NeT, as well as further developments of this technology for future applications.

Together with the Royal Dutch Institute for Sea Research (NIOZ) Nikhef developed and validated the deployment launcher vehicle that allows for unfurling of the detection strings from the seabed, overall leading to a much lighter structure, less influenced by the sea currents.

As the string-like unit is influenced by the sea current, it is crucial to keep the hydrodynamic drag to a minimum. This required another Nikhef innovation: the vertical electro-optical cable. This cable is a pressure balanced oil-filled cable with a diameter of only 7 mm. It houses the electrical wires to provide power to the photo multiplier tubes and the readout electronics as well as the optical fibres for communication to shore. This cable, which replaces costly conventional cabling and connectors, is now being produced in Dutch industry under supervision of Nikhef.

The first production facility for optical modules is based at Nikhef. Integration of the first two detection lines was done in the production facility in our workshop. In the meantime, the know-how has been transferred to five other production sites throughout Europe, all of which are building the Nikhef DOM design.

The next phase of KM3NeT (KM3NeT 2.0), described in the Letter of Intent, was placed on the roadmap of the 2016 European Strategy Forum for Research Infrastructures (ESFRI). It has also been placed on the Dutch National Roadmap for Large Research Infrastructures. In the framework of Horizon 2020, KM3NeT has recently received a grant for building a legal entity in terms of an ERIC. The collaboration has agreed that the headquarters of this ERIC should be in Amsterdam. In addition, the grant provides funding for a study into making KM3NeT a carbon-neutral facility. The fact that the location deep below the sea has required significant energy efficiency, makes the goal of carbon neutrality feasible.

National and International collaborations

Within the Netherlands, Nikhef collaborates with CART (Groningen), Royal Dutch Institute for Sea Research (NIOZ), and the TNO institute in Delft. All are also members of the KM3NeT collaboration. We have regular short-term visits of students from, in particular IFIC, Valencia and APC, Paris. Within Nikhef, people interested in neutrino research have started to have regular meetings; we foresee that the KM3NeT activity can be the seed of a larger Nikhef activity, which includes participation in future accelerator based neutrino experiments (in particular DUNE). We have also initiated collaboration with the Nikhef theory group to compute high energy neutrino cross-sections. This is of relevance for neutrino astronomy, but will also allow for the use of neutrinos as a novel way to probe QCD.

The technology of KM3NeT is finding its way to other experiments. IceCube is considering building Multi-PMT optical modules for a future upgrade. A Memorandum of Understanding between KM3NeT and Hyper-Kamiokande has been signed which provides collaboration on both Multi-PMT technology and low-energy neutrino event generators. Via P. Kooijman, KM3NeT timing and readout electronics is used in the Chips experiment.

The four neutrino telescope projects in the world, ANTARES, BAIKAL, IceCube and KM3NeT, signed a Memorandum of Understanding (MoU) for collaboration in a Global Neutrino Network (GNN). The MoU aims at implementing a coherent programme of schools, topical workshops and early-career awards to strengthen the global neutrino telescope community and define common research strategies.

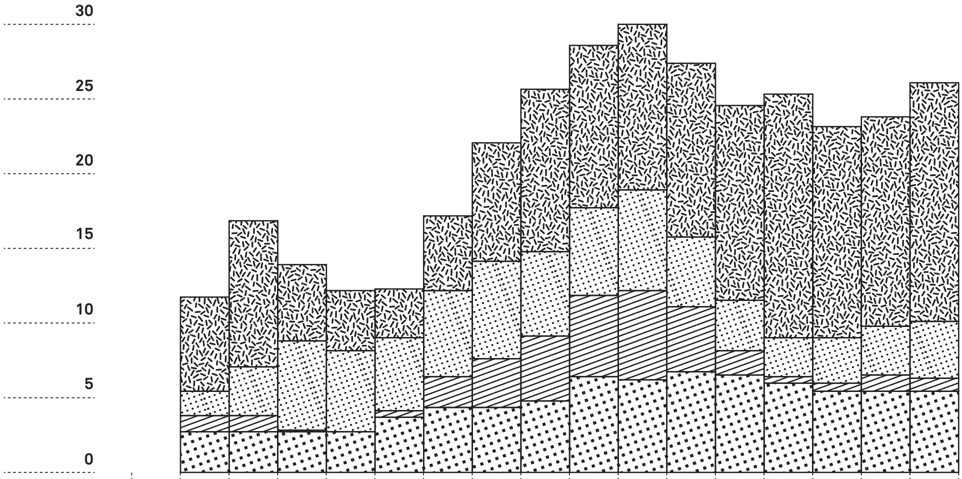
Grants and Awards

→ E-science pathfinder grant: 2015 - D. Samtleben & R. Bruijn
→ NWO VICI Award: 2017 - A. Heijboer
→ H2020 Grant: 2016 - PI: M. de Jong
→ Participant in LOWE-NU (3rd ASPERA common call)
→ Participant in ASTERICS

Key Publications

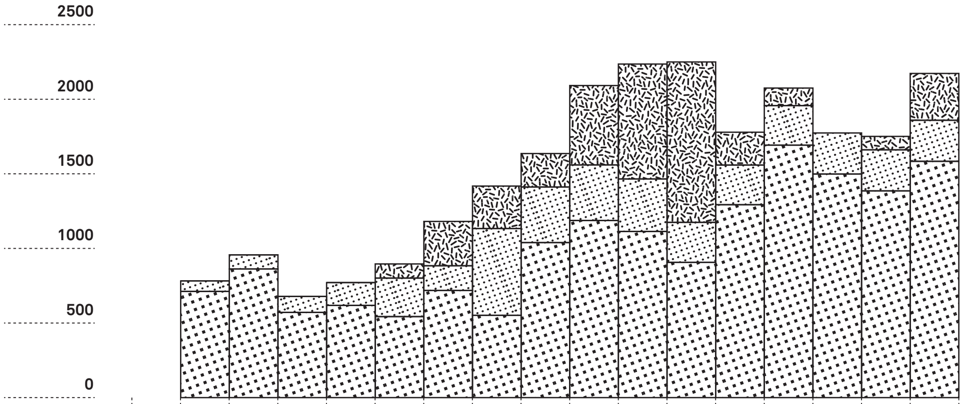
1. S. Adrián-Martínez et al. (KM3NeT Collaboration), *"Letter of intent for KM3NeT 2.0"*, J.Phys. G43 (2016) no.8, 084001.
2. S. Adrián-Martínez et al. (KM3NeT Collaboration), *"Deep sea tests of a prototype of the KM3NeT digital optical module"*, Eur.Phys.J. C74 (2014) no.9, 3056.
3. S. Adrián-Martínez et al. (ANTARES Collaboration), *"First Search for Point Sources of High Energy Cosmic Neutrinos with the ANTARES Neutrino Telescope"*, Astrophys. J. 743 (2011) L14.
4. S. Adrián-Martínez et al. (ANTARES Collaboration), *"Search for Cosmic Neutrino Point Sources with Four Year Data of the ANTARES Telescope"*, Astrophys. J. 760 (2012) 53.
5. S. Adrián-Martínez et al. (ANTARES and IceCube and LIGO Scientific and VIRGO Collaborations), *"High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube"*, Phys.Rev. D93 (2016) no.12, 122010.

FIGURE 15 **Antares/KM3NeT manpower** (in fte)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical staff		5,8	9,0	4,7	3,7	3,0	4,6	7,3	10,0	10,0	10,2	10,7	12,0	15,0	13,0	12,9	14,7
PhD students		1,5	3,0	5,5	5,0	4,5	5,3	6,0	5,2	5,4	6,2	4,3	3,1	2,4	2,8	3,0	3,5
Postdocs		1,0	1,0	0,1	0,0	0,4	1,9	3,0	4,0	5,0	5,5	4,0	1,5	0,4	0,5	1,0	0,8
Staff		2,5	2,5	2,5	2,5	3,4	4,0	4,0	4,4	5,9	5,7	6,2	6,0	5,5	5,0	5,0	5,0

FIGURE 16 **Antares/KM3NeT budget** (in k€)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects		0	0	0	0	95	297	285	224	532	770	1075	220	118		90	314
Universities		70	95	107	153	258	166	581	373	373	352	268	266	265	275	275	275
FOM-university groups		712	862	571	618	543	718	552	1039	1187	1114	907	1293	1692	1499	1386	1584

GRAVITATIONAL WAVES

Programme organization
Programme leader:
→ prof. dr. J.F.J. van den Brand
University partners:
→ VU, RU

Research Goals

The primary objective is the direct detection of gravitational waves with the ground-based LIGO and VIRGO interferometers. Detectors capable of observing binary black hole and neutron star mergers have an enormous impact in several key scientific areas. Moreover, these gravitational wave observations are firmly embedded in the wider field of fundamental physics, astronomy, astrophysics and cosmology. Enhancing detection performance with Einstein Telescope and LISA will make it possible to continuously observe the distant, dark, dense and catastrophic nature.

Research Highlights

The first direct detection of gravitational waves (GW) with LIGO happened on 14 September 2015, and was named accordingly GW150914. The event was identified as extremely promising already on the day itself, and shortly afterwards its significance was established to be $> 5.1\sigma$. Follow-up analyses revealed that it had most likely resulted from the merger of two black holes of 36 and 29 solar masses; no less than 3 solar masses worth of energy was emitted in gravitational waves, making this the most powerful event ever observed by mankind. Also at the detectors, it was sufficiently loud to be visible by eye in the raw data. The detection represented several scientific breakthroughs at once: apart from being the first direct GW detection, it provided the first direct evidence of the existence of black holes; it was also the first observation of a binary black hole merger, and it finally gave us access to the genuinely strong-field dynamics of pure spacetime. A second clear detection came on 26 December 2015, called GW151226, involving black holes of 14 and 8 solar masses.

Nikhef contributions

The Nikhef group played an important role in the analyses of GW150914, in a variety of ways. J. van den Brand was a member of the

Detection Committee of the LIGO VIRGO Collaboration, which had been charged with checking all aspects of the process that led to the discovery of GW150914, from the instrumentation (including the possibility of malicious tampering) to the final data analysis products. C. Van Den Broeck was VIRGO Data Analysis Coordinator, in which role he helped organize the joint LIGO-VIRGO analysis activities, together with his counterpart in the US. Furthermore, during the preceding 5 years, Nikhef had been spearheading the development of methods for testing general relativity (GR) using GW signals from merger events, which could now be applied to real detections. Finally, G. Nelemans helped in interpreting the events from an astrophysics point of view: the unexpectedly high masses of the black holes in GW150914 implied that they had formed in a low-metallicity environment.

GW150914 was what is known as a "golden event", meaning one whose total mass was such that the black hole merger occurred at a frequency where the detectors are the most sensitive. It starts with two black holes spiraling towards each other as orbital kinetic energy and angular momentum are radiated away in gravitational waves. At some point a last stable orbit is reached, and the black holes plunge towards each other and merge to form a single, highly excited black hole. The latter will shed its excitations ('ringdown'), and finally settles down into a dormant state. The early inspiral is understood perturbatively through the so-called post-Newtonian formalism, in which e.g. the GW phase can be written as an expansion in powers of v/c (with v the characteristic velocity and c the speed of light). In earlier kinds of observations (e.g. radio observations of binary neutron stars), only the leading-order post-Newtonian contribution could be measured with any kind of accuracy; already with GW150914, for the first time bounds could be put on potential violations of GR in high-order post-Newtonian coefficients. Moreover, observables related to the pre-merger and merger-ringdown regimes could be constrained. GW150914 and GW151226 yielded complementary information: the former revealed the strongly non-linear behaviour of spacetime near merger, while the latter, with its much longer inspiral signal in the sensitive frequency band, enabled precision tests of the inspiral of binary objects. One of the most important post-Newtonian parameters is the one at $(v/c)^3$ beyond leading order, which incorporates the dynamical self-interaction of spacetime. This coefficient has now been constrained to 10%; towards the end of the decade, as information from a growing number of detections can be combined, this uncertainty will likely shrink to the 1% level. These results will be part of the PhD thesis of Nikhef student J. Meidam.

If it turns out that gravity is described by a quantum field theory, the graviton is the particle that transmits the force of gravity. VU PhD student M. Agathos has used the data to put a bound on the mass of the hypothetical graviton. A non-zero value of this mass would be noticeable in a classical gravitational wave: the higher-frequency components would be traveling slightly faster than the low-frequency ones, and both slower than the speed of light. This effect is cumulative over the huge distance (in this case 1.3 billion lightyears) that the wave has to travel from source to detector, so that a sharp measurement can be made. This led to the strongest dynamical bound on the graviton mass yet obtained: $mg < 1.2 \times 10^{-22}$ eV/c^2, the first ultra-high precision result to come from gravitational wave physics. The paper summarizing these and other tests of GR that were performed was the most cited research publication of the LIGO-VIRGO Collaboration for 2016, second only to the two detection papers themselves.

Nikhef contributions to the Advanced Virgo detector

The upgrade of Virgo to a second generation gravitational wave detector, the Advanced Virgo project, was brought to completion in 2016. The upgrade has involved the majority of the detector subsystems, with Nikhef giving a decisive contribution to many of them. Nikhef investments in Advanced Virgo were through an NWO-Groot Grant in 2012, *Advanced Virgo – Probing the dynamics of spacetime:* 2 M€, in combination with a 1.5 M€ investment from Nikhef's Mission Budget, corresponding in total to 14 % of the investment in the Advanced Virgo upgrade project.

Advanced Virgo will operate with increased laser power circulating in the interferometer arm cavities (from 20 kW to 700 kW), which allows reducing the photon shot noise by more than one order of magnitude. Practical implementation requires to compensate the thermally induced distortion and the optical defects in the input optics (i.e. the power recycling mirror and input test masses). Such aberrations would in fact spoil the matching between the laser and the power recycling cavity, e.g., the power sent to the interferometer beamsplitter, preventing to reach the designed shot noise figure. A complex adaptive optics system, called Thermal Compensation System (TCS), has therefore been realized for Virgo, based on different types of wavefront sensors and non-contacting thermal actuators, to statically and dynamically correct the aberrations.

Among the TCS wavefront sensors, the most peculiar ones are the three Phase Cameras developed and realized at Nikhef which allow to compare, with sub-nanometre level resolution, the wavefront of the input laser beam with that of the beam circulating in the interferometer. The last one carries imprinted the input optics aberrations that then are measured and can corrected by means of the TCS actuators. In the second half of 2016 the three phase cameras have been installed and integrated into the detector, and they are now already providing crucial reference signals during the commissioning of the machine.

Nikhef also designed and produced the optical sensors, shot noise limited DC and RF quadrant photodetectors, used in the angular alignment system of Virgo to maintain the relative orientation of all suspended optical elements within the required few nano-radians accuracy. Nikhef's instrument makers have also designed and produced dedicated high-vacuum compatible galvo-scanners needed to center the beam on the RF quadrants for the differential wavefront sensing. All these components are in service on the Virgo auxiliary optical benches since mid-2016.

In Advanced Virgo, the decision was taken to have all auxiliary optical benches in vacuum and vibration isolated in order to reduce the seismic noise coupling to the angular alignment sensor signals and the coupling to the interferometer output through the light scattered by the sensors themselves and by their associated pick-off telescopes. This required five multistage seismic attenuation systems (so-called MultiSAS) to be designed and built at Nikhef. All MultiSAS units, each of them providing more than six orders of magnitude vibration isolation in all six degrees of freedom, have been integrated into the detector and the two of them located behind the interferometer end mirrors are fully operational since summer 2016.
The remaining three units, now temporarily disabled, are planned to also be operational during the first observation run.

The cryogenic vacuum links, the major infrastructure upgrade of the detector, also designed at Nikhef, have proven, in their first year of continuous operation started at the end of 2015, to be very effective in reducing the residual gas pressure in the interferometer arms (the largest vacuum system in Europe with its nearly 6000 m^3 volume) well below the water vapour limit. Reaching vacuum pressures below 10^{-9} mbar is of paramount importance for the successful operation of Advanced Virgo, the sensitivity of which would otherwise be limited by the phase noise caused by the random scattering of the laser beam from the residual gas molecules.

Collaborations with Theory

At Nikhef there is an ongoing collaboration with colleagues of the theory group, under the leadership of prof. J.W van Holten. These collaborations have resulted in 6 publications that included new approaches on the motion of neutral and charged spinning bodies in curved spacetime in the test-particle limit. To have in-house theory expertise is a strong asset for Nikhef.

Leadership positions in the collaboration

The prominence of the Nikhef group in gravitational waves research can be recognized by the fact that Nikhef is deeply involved in analyses and sub-detector constructions and is reflected in project leadership positions as well as coordination positions:

- → Virgo Data Analysis Coordinator (C. Van Den Broeck) 2014-2016
- → LIGO-Virgo infrastructure group on tests of general relativity (C. Van Den Broeck) 2016-present

International Scientific Advisory Committees:

- → ApPEC (J. van den Brand): 2013 - now
- → KAGRA (J. van den Brand): 2014 - now
- → NWO Computing Science for Energy Research (J. van den Brand)
- → LIGO Virgo Collaboration Project Leaders and coordinators:
    - → LIGO Virgo Detection Committee (J. van den Brand) 2015- now
    - → Virgo Data Analysis Coordinator (C. Van Den Broeck) 2014-2016
    - → Virgo Suspended Benches (A. Bertolini) 2011-2016
- → Einstein Telescope Governing Council: 2009 - now (J. van den Brand)

- LISA coordination:
  - International Board (G. Nelemans)
  - Dutch National Board 2015 - (N. van Bakel, G. Nelemans (chair), J. van den Brand)

Grants, Awards and Patents

- Physica Prize of the Netherlands' Physical Society: 2017 – J. van den Brand
- Gruber Cosmology Prize: 2016 - LIGO Virgo Collaboration
- Special Breakthrough Prize in Fundamental Physics: 2016 - LIGO Virgo Collaboration
- Stefano Braccini Thesis Prize: 2013 - Li
- Jan Kluyver-prize : 2011 – G. Koekoek
- Volkert van der Willigenbeurs: 2016 - Janna Goldstein
- NWO Physics Valorisation Prize: 2015 – J. van den Brand
- NWO VICI Award: 2015 – G. Nelemans
- NWO VIDI Award:
  - 2015 – S. Nissanke
  - 2015 – S. Bernuzzi
- NWO Rubicon Award:
  - 2016 – Agathos
  - 2013 – Li
- FOM Projectruimte: 2015 – C. Van Den Broeck
- NWO TOP Grant: 2015 – S. Nissanke
- FOM-Computing Science Energy Research: 2014 – H.J. Bulten
- Marie Curie Fellowship: 2017 - Dietrich
- FOM Valorisation Chapter Prize: 2014 – M. Beker
- Patents:
  - *MEMS sensor structure comprising mechanically preloaded suspension springs,* inventors: J.F.J. van den Brand, E. Hennes and A. Bertolini; owners: Stichting VU-VUmc en FOM-Nikhef. The invention relates to a MEMS structure comprising one or more mechanically preloaded suspension springs, and, in particular, though not exclusively, an inertial MEMS sensor comprising mechanically preloaded suspension springs and a method for mechanically preloading suspensions springs in an MEMS sensor. EP 18979-Vi/td, 2013

- *Location-based broadcast protocol and time slot schedule for a wireless mesh* Network, inventors: J.F.J. van den Brand and H.J. Bulten; owners: Stichting VU-VUmc en FOM-Nikhef. The invention relates to a broadcast protocol for a wireless mesh network, and, in particular, though not exclusively, to a method for managing communication in a wireless mesh network comprising a plurality of wireless nodes, and a computer program product using such method. EP 18978-Vi/td, 2014

Key Publications

1 B.P. Abbott et al., *Observation of Gravitational Waves from a Binary Black Hole Merger.* By LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 116 (2016) 061102. e-Print: arXiv:1602.03837 [1255 citations as of April 1, 2017]

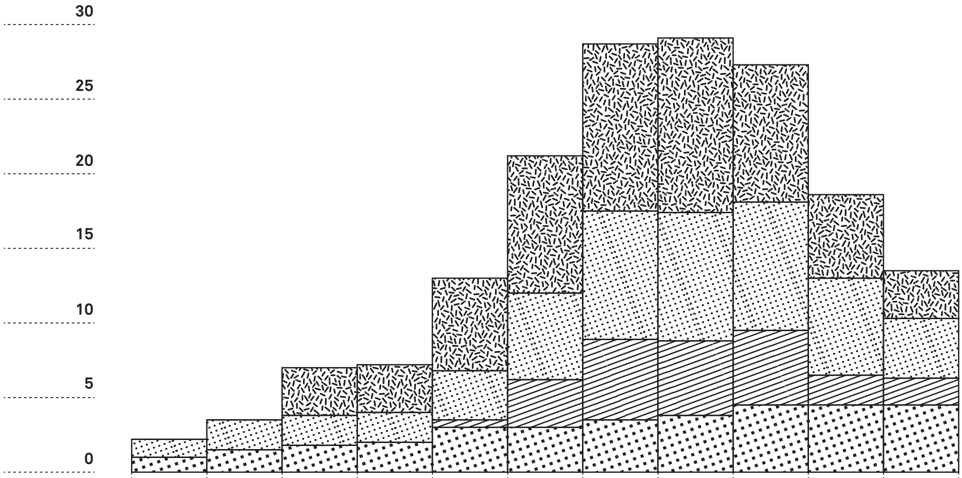
2 B.P. Abbott et al., *GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence.* By LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 116 (2016) 241103. e-Print: arXiv:1606.04855 [389 citations as of April 1, 2017]

3 B.P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo.* By LIGO Scientific Collaboration and Virgo Collaboration, Living Rev. Rel. 19 (2016) 1. e-Print: arXiv:1304.0670 [331 citations as of April 1, 2017]

4 F. Acernese et al., *Advanced Virgo: a second-generation interferometric gravitational wave detector.* By LIGO Scientific Collaboration and Virgo Collaboration, Class. Quant. Grav. 32 (2015) no.2, 024001. e-Print: arXiv:1408.3978 [291 citations as of April 1, 2017]

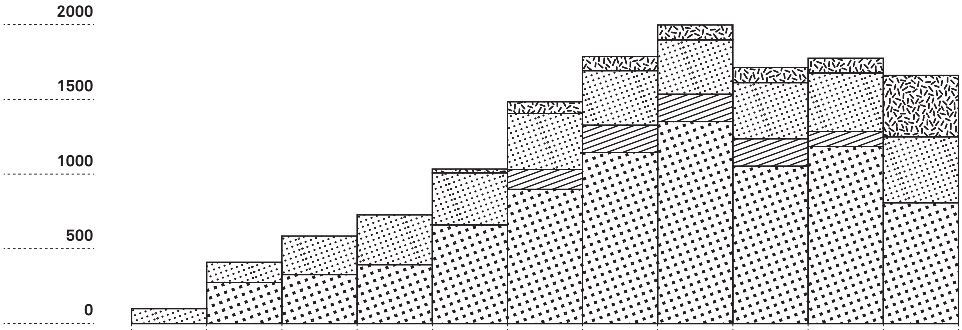
5 B.P. Abbott et al., *Tests of general relativity with GW150914.* By LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 116 (2016) 221101. e-Print: arXiv:1602.03841 [180 citations as of April 1, 2017]

FIGURE 17 **Gravitational Waves manpower** (in fte)



	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical staff	0,0	0,0	3,2	3,2	6,2	9,2	11,2	11,7	9,2	5,6	3,2
PhD students	1,2	2,0	2,0	2,0	3,3	5,8	8,6	8,6	8,6	6,5	4,0
Postdocs	0,0	0,0	0,0	0,0	0,5	3,2	5,4	5,0	5,0	2,0	1,8
Staff	1,0	1,5	1,8	2,0	3,0	3,0	3,5	3,8	4,5	4,5	4,5

FIGURE 18 **Gravitational Waves budget** (in k€)



	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects					26	78	95	100	102	99	411
Universities	100	136	258	333	348	374	364	363	375	391	441
FOM-university groups						133	183	183	183	101	
FOM-Nikhef		275	328	394	660	898	1144	1351	1053	1184	808

COSMIC RAYS

Programme Organization

Programme leader:

- dr. Charles Timmermans (2011-2013), prof. dr. S. de Jong (2013-present)

University partners:

- RU

Research Goals

The most energetic particles observed in our universe are cosmic rays, which have been measured with energies in excess of 10^{20} eV (=100 EeV). The origins of, and acceleration mechanisms leading to, these ultra-high-energy cosmic rays are yet unknown. These cosmic rays should interact with the cosmic microwave and other cosmic backgrounds producing photons and neutrinos that have never been observed. Ultra-high-energy cosmic rays interact with the atmosphere in hadronic interactions with centre-of-mass energies exceeding those of human accelerators (i.e. the LHC) by more than an order of magnitude, i.e. in a region where the Standard Model largely remains untested so far.

The goals of this research programme are to detect ultra-high-energy cosmic rays, including photons and neutrinos, with the best measurement of energy, arrival direction, and composition information to search for point sources of ultra-high-energy cosmic rays, understand their acceleration mechanisms, study their interactions with the cosmic background, and the physics at the highest observable particle interaction energy from their collision with atmospheric nuclei.

Research Highlights

- Surface Detector measurements
  - Determination of the mass composition of ultra-high-energy cosmic rays with the Auger Surface Detector
- Radio Detection of high-energy cosmic rays
  - Construction, commissioning and exploitation of the Auger Engineering Radio Array, covering 17 km^2
  - Understanding of the lateral density profile of radio frequency radiation from high-energy extensive air showers

  - → Absolute energy calibration of radio detection of high-energy cosmic rays
- → Determination of the mass composition of ultra-high-energy cosmic rays with radio detectors

Research Activities

The research has so far been conducted in the context of participation in the Pierre Auger Observatory. This is a hybrid detector using a Surface Detector (SD) of more than 1600 water Cherenkov detector stations, spaced in a triangular grid with 1.5 km inter-detector station distance, covering in total 3000 km^2 of the Pampa Amarilla in the province of Mendoza in Argentina. The SD is active 24/7, in its completed form since 2008.
The Fluorescence Detector (FD) observes the atmosphere above the SD area. There are four FD stations arranged around the SD area, each consisting of six fluorescence telescopes in a semi-circle arrangement. At one of the FD stations, three additional fluorescence telescopes are looking at higher elevations (HEAT). The FD (and HEAT) can only operate at dark nights with few clouds, which is about 13% of the total time.

The Pierre Auger Collaboration firmly established the end of the cosmic-ray energy spectrum, more or less exactly at the energy predicted by the Greizen-Zatsepin-Kuz'min (GZK) effect. However, more detailed studies, many of them in the period from 2011 until now, have cast serious doubt of the GZK effect as the only responsible mechanism for the end-point of the spectrum. In the GZK case the composition at the end of the spectrum should consist of a large fraction of protons. Extrapolations of observations at slightly lower energies seem to indicate a heavier composition. This hints at the end-point being reached because of a maximum energy that can be reached by cosmic accelerators. Unfortunately, no composition information at the end of the spectrum is available yet.

Early hints of point sources of ultra-high-energy cosmic rays could not be confirmed with much more data that has been collected. Hints of anisotropy are remaining at the level of 2.5-3σ. A large-scale anisotropy for energies around 1-10 EeV is observed that steadily increases in significance.

Nikhef Contributions

A joint cosmic ray group from Nikhef, comprising the Experimental High Energy Physics and Astronomy departments of the Radboud University Nijmegen, and KVI-CART of the University of Groningen joined the Pierre Auger Collaboration in 2005. The Dutch group has made small contributions to the construction and commissioning of the observatory, it being in the final stages of construction when joining. The Dutch group has participated at full strength in running the observatory, notably in performing Fluorescence Detector shifts. From the onset the Dutch group has focused on a new detection technique: radio detection. Radio frequency signals from air showers had already been observed in the 1960's. However, that detection method was largely abandoned after a while and it took until the 2000s for radio detection to be revived by a seminal paper of H. Falcke and P. Gorham and with a crucial test of the LOPES array at the KASCADE-Grande ground array. Since 2005 the Dutch group has played the leading role in radio detection in the Pierre Auger Observatory. First with the MAXIMA test set-up, containing four radio detector stations, and later in the Auger Engineering Radio Array (AERA), which is led by one of the Dutch group members, J. Hörandel.

A lot of experience has been gained on the road to the autonomous radio detector stations that have been deployed in AERA. Several antenna designs have been used and power harvesting and storage have been incorporated, as well as wireless communications of the stations in the data acquisition system. A trigger on the radio detector information alone, assisted by small scintillator counters that are mounted in the radio detector stations, was also tested.

The programme has also profited much from close ties to the LOFAR key science project Cosmic Rays. In LOFAR, the antennas of the core are used, complemented with a scintillator array, LORA, for triggering. The high density of antennas in LOFAR has allowed for a good theoretical understanding and modelling in Monte Carlo programmes of the radio frequency signal. This knowledge has been fruitfully applied to the AERA set-up.

After the pioneering work of the PhD students S. Harmsma and J. Coppens on the MAXIMA test set-up with only four antenna stations, other PhD students from our group have been able to harvest and bring the comprehension of radio detector forward in big steps. H. Schoorlemmer and D. Fraenkel have been able to distinguish the two emission contributions by studying the polarization patters on the signal. S. Grebe and S. Jansen have been able to calibrate the stations to such a detail that they could derive composition information from the spectral behaviour of the signal using even a single detector station. K. de Vries has been able to advance the theoretical understanding and modelling of the radio frequency emission using the AERA results. A. Nelles has invented a heuristic parameterization of the lateral signal distribution that has enabled precise energy measurements and composition determination of the incoming cosmic ray, work that was further advanced by J. Schulz. As a postdoc J. Kelly made key contributions to both, hardware and radio frequency emission modelling. From the senior staff, O. Scholten of KVI-CART made crucial theoretical contributions to the modelling of the signal, J. Hörandel leads the AERA project, Charles Timmermans made crucial hardware contributions and A. van den Berg, H. Falcke and S. de Jong contributed to hardware development, installation and commissioning and guiding analyses by the PhD students. There are many things that can still be learnt from the AERA data. Further studies are done by the PhD students F. Canfora and B. Pont.

Following the advice of the previous evaluation and the Nikhef Scientific Advisory Committee, the Nikhef group also got involved in mainstream analysis of the Pierre Auger Collaboration. The PhD student G. van Aar has been able to extract composition information from the SD, which he applied to derive the mass composition at significantly higher energy than was accessible with the FD. These new points confirm the trend away from light mass composition when going towards the end-point of the energy spectrum. The SD mass composition analysis is being pursued further in the programme by the PhD students G. de Mauro and A. Aab. S. Messina has calibrated AERAlet, a high-sensitivity infill of the SD at the AERA location. Subsequently he was able to extend the energy spectrum measurement by the Pierre Auger Collaboration to lower energies, down to 0.01 EeV, filling the gap with measurements at lower energy of earlier and smaller experiments.

National and international collaborations

The Dutch group comprises Nikhef groups from the experimental high-energy physics and astronomy departments of the Radboud University Nijmegen, and a group from KVI-CART at the University of Groningen. These groups operate as one unit in the Pierre Auger Collaboration.

The Radboud University group has strong links with the ASTRON led LOw Frequency ARray (LOFAR) radio telescope, with H. Falcke the chair of the LOFAR international board and J. Hörandel the PI of the LOFAR key science project Cosmic Rays.

The Pierre Auger Collaboration, which has built, commissioned and is operating the Pierre Auger Observatory, comprises 69 universities and institutions from 16 countries, with about 400 scientists being a member of the collaboration.

C. Timmermans and S. de Jong are also involved in the proto-collaboration GRAND, Giant Radio Array for Neutrino Detection, together with scientists from France, China, the USA, and other countries.

Grants and Awards

- NWO Spinoza Award: 2011 – H. Falcke
- ERC Synergy Grant: 2013 – H. Falcke
- Elected to Royal Netherlands Academy of Arts and Sciences (KNAW): 2013 – H. Falcke
- Elected to Academia Europaea:
    - 2013 – H. Falcke
    - 2016 – S. de Jong
- Knight in the Order of the Netherlands Lion:
    - 2015 – S. de Jong
    - 2016 – H. Falcke
- President of the CERN Council: 2015 – S. de Jong

Key Publications

1 A. Aab et al. (The Pierre Auger Collaboration), *"Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory"*, Phys.Rev. D93 (2016) 122005. [29 citations]

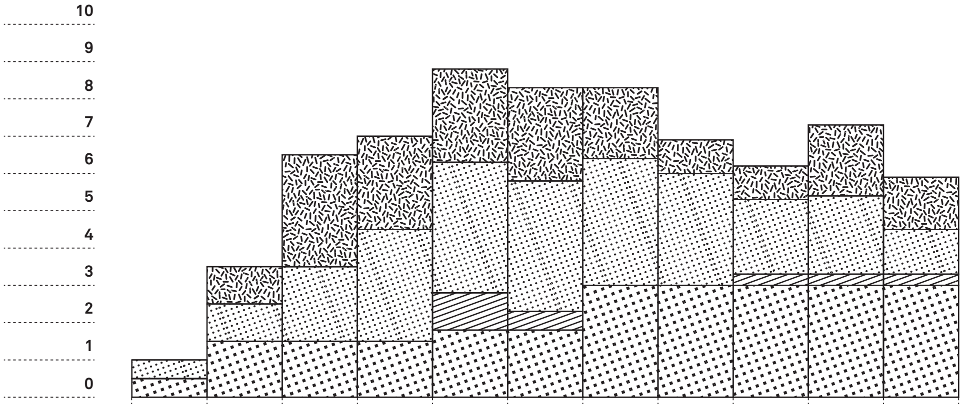
2 A. Aab et al. (The Pierre Auger Collaboration), *"The Pierre Auger Cosmic Ray Observatory"*, Nucl.Instr.Meth. A798 (2015) 172. [134 citations]

3 A. Aab et al. (The Pierre Auger Collaboration), *"Depths of Maximum of Air-Shower Profiles at the Pierre Auger Observatory: Composition Implications"*, Phys.Rev. D90 (2014) 122006. [131 citations]

4 A. Aab et al. (The Pierre Auger Collaboration), *"Probing the radio emission from cosmic-ray-induced air showers by polarization measurements"*, Phys.Rev D89 (2014) 052002. [70 citations]

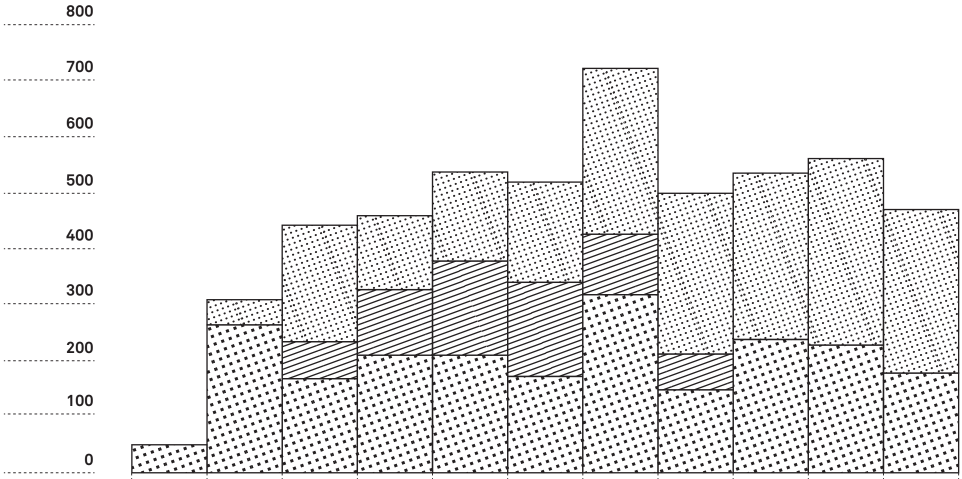
5 A. Abreu et al. (The Pierre Auger Collaboration), *"Measurement of the proton-air cross-section at $\sqrt{s}$=57 TeV with the Pierre Auger Observatory"*, Phys.Rev.Lett. 109 (2012) 062002. [173 citations]

FIGURE 19 **Auger manpower** (in fte)



	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical staff	0,0	1,0	3,0	2,5	2,5	2,5	1,9	0,9	0,9	1,9	1,4
PhD students	0,5	1,0	2,0	3,0	3,5	3,5	3,4	3,0	2,0	2,1	1,2
Postdocs	0,0	0,0	0,0	0,0	1,0	0,5	0,0	0,0	0,3	0,3	0,3
Staff	0,5	1,5	1,5	1,5	1,8	1,8	3,0	3,0	3,0	3,0	3,0

FIGURE 20 **Auger budget** (in k€)



	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Universities		45	208	132	159	179	296	287	297	333	292
FOM-university groups			66	117	168	168	108	64			
FOM-Nikhef	50	264	168	210	210	172	318	148	238	228	178

DARK MATTER

Programme organization
Programme leader:
→ prof. dr. M.P. Decowski
University partners:
→ UvA

Research Goals

The main research goal of the Dark Matter group is to discover, and characterize, the particle responsible for the dark matter observed in the nature. We pursue our research goals through the design, operation and analysis of ultra-sensitive low-background experiments using liquid xenon targets at INFN's Laboratori Nazionali del Gran Sasso (LNGS) underground laboratory in Italy and with R&D work in our local laboratory at Nikhef.

Research Highlights

The chief highlight of the Nikhef Dark Matter group over the past years is the completion of the XENON1T dark matter experiment and the start of its scientific exploitation in Fall 2016. XENON1T will be the world's most sensitive direct detection dark matter experiment until the start of the next-generation dark matter experiments in 2020. The experiment has two orders of magnitude better sensitivity than XENON100, its predecessor, with a real possibility of discovering the dark matter particle. While our group was building XENON1T, we were also part of the XENON100 analysis team, participated in the DARWIN design study and we designed and constructed a xenon R&D setup at Nikhef.

Research Activities

Our research activities are separated into several experimental projects, but all share the basic detection methodology of using dual-phase (liquid/gas) xenon time project chambers (TPCs) of varying size. Members of our group typically participate in more than one project at a time. Below we list our activities in order of effort.

XENON1T design, construction and analysis

Our main focus over the past years has been the design and construction of the XENON1T experiment. The Nikhef experimental dark matter group was invited to join the XENON collaboration in 2010 and has become a leading player since then. The XENON1T experiment was approved for construction at the Gran Sasso underground laboratory in April 2011. Our group has led the development and taken responsibility in the following areas: 1) detector alignment and support system, 2) data acquisition (in particular the trigger), and 3) the data processing software. In addition, we played important roles in the design of the cryostat, cryo-pipe and the calibration systems. The construction of XENON1T started in September 2013 and was completed at the end of 2015. After a few months of commissioning the cryogenic systems, the detector was filled with 3.2 t of liquid xenon in April 2016 and has remained filled since. The experiment started the first science run in October 2016.

Members of the Nikhef group have played key roles in the collaboration. We (co-)led the Cryostat and Support Structure Working Group (A.P. Colijn) and Data Acquisition Working Group (M.P. Decowski) during the construction. We also participated in several engineering reviews (A.P. Colijn, M. Doets, R. Walet). One of us has served on the five-member XENON Editorial Board overseeing all XENON100 and XENON1T publications during the past six years (M.P. Decowski, currently serving as chair). A.P. Colijn was the Run Coordinator at the start of the first science data coming from XENON1T. Finally, one of our postdocs (C. Tunnell) became the first XENON1T physics analysis coordinator and is currently leading the first XENON1T analysis. The Nikhef postdocs and PhD students have initiated, and developed, the XENON1T data processing software PAX, which has been adopted by the collaboration as the official data processing software. Our PhDs have also played leading roles towards the analysis of the first XENON1T data, focusing on core analysis issues such as event classification, signal and background modelling and their statistical interpretation (J. Aalbers), background estimation, fiducial volume optimization (S. Breur) and neutron recoil calibration (E. Hoogenbirk).

XENON100 Operations and Analysis

Over the past years, we participated in the operation and analysis of data from XENON100. This detector, with and active xenon mass of ~65 kg, was operational until Summer 2016. The focus of the Nikhef group was the analysis of low-mass WIMPs through an "S2-only" analysis that allows for a lower energy threshold. Our group led this analysis (C. Tunnell and PhD student A. Tiseni), which resulted in a paper published in PRD. Other items we worked on were: a very low energy neutron calibration of XENON100 with an Y-Be neutron source and the development of a method to use double-scatter events for energy calibration.

XAMS R&D detector at Nikhef

In order to be able to study dual-phase xenon TPCs and detection techniques in our own lab, we built a xenon R&D setup at Nikhef. This setup, named XAMS, has an active xenon mass of 0.5 kg and a full xenon purification and recirculation system. The TPC was built in a modular fashion to ease the adaptation of the geometry if necessary. The system was completed in 2014 and our commissioning results were published in a NIM paper in 2016. The setup uses the same DAQ and data processing software developed by us, and used in, XENON1T and has already proven to be valuable to recruit and train students.

XENONnT

Most XENON1T systems were designed with an upgrade path to XENONnT, with roughly double the amount of xenon and PMTs compared to XENON1T, right from the beginning. Our group realized the possibility that the large amount of xenon in XENONnT could allow for a meaningful search for neutrinoless double beta decay ($0\nu 2\beta$) in ^{136}Xe. Our group therefore initiated a study to determine the XENONnT $0\nu 2\beta$ sensitivity with a realistic detector and backgrounds, showing that indeed XENONnT could obtain $0\nu 2\beta$ results competitive with other $0\nu 2\beta$ experiments. Since the relevant energy scales are different for a DM search and a $0\nu 2\beta$ search, a different readout scheme will be necessary. Together with Nikhef's ET department, we designed, prototyped and tested an amplifier that could be used in XENONnT readout to allow for the $0\nu 2\beta$ search in conjunction with the dark matter data taking.

DARWIN design study

Our group has been involved in the DARWIN design study since 2010. This design study envisions an "ultimate" ~50 t dual-phase liquid xenon detector that would explore the full experimentally accessible WIMP parameter space. We initially studied the use of GridPix (a micro-pattern gaseous detector developed at Nikhef) as a possible charge (S2) readout system in DARWIN. In 2014-2016, we focused on studying the scientific performance, including signals other than dark matter, of the DARWIN facility.

Nikhef Contributions

We list here our technical contributions to XENON1T:

- Detector alignment and support system; this structure ensures that the free-hanging cryostat is properly supported at the center of the water tank. It also has to decouple any ground vibrations from the cryostat. In addition, before data can be taken with the detector, the multi-ton detector has to be levelled to better than 100 μrad. Our system takes care of all of the above and is designed to XENONnT specifications, so it can be directly used in the new facility.
- Event builder and trigger; this is at the heart of the readout system, all the data that the XENON project generates passes through this system. We proposed and realized the implementation of a "trigger-less" system to the XENON collaboration. The Nikhef software finds the events in the data stream that pass certain conditions (trigger) and then combines all the data into a usable structure, possibly pre-scaling uninteresting events (event building) and writes these out to data files for further processing. The system has been successfully operated for over a year and is fully scalable and will be re-used for XENONnT. While the software is specifically written for our application, we use industry-standard computing and database tools in its implementation.
- Data processing software; we proposed and fully developed the new data processing system that is used in XENON1T and is ready for XENONnT. This includes low-level analysis such as PMT signal conditioning and peak finding, but also higher level reconstruction such as position reconstruction, event classification and energy calibration. This software is the core software used by the XENON collaboration for data analysis. Also here we made a transition from standard C++ and ROOT-based tools towards python-based software that is used in a wider scientific and industrial environment.

There are also a number of other areas where we have contributed significantly, especially with a number of engineering projects:

- → Mechanical design of the cryostat and cryo-pipe; we originally proposed the mechanical design of the cryostat and cryo-pipe. While the responsibility of the system was with Columbia University, we were regularly consulted and participated in the reviews. We made significant contributions to the overall design, using the cryogenic expertise of Nikhef's engineering department.
- → Concept and design of the calibration source transportation system; while the responsibility of the Calibration system is with Purdue University, we designed and provided the detailed engineering drawings for the radioactive source and neutron generator deployment systems.
- → GRID Computing; we initiated the use of GRID computing in XENON and provide the largest GRID computing share through a SURFNet E-infra allocation.

National and International Collaborations

International: Our group participates in the XENON collaboration consisting of 130 collaborators at 22 institutions mostly in Europe and in the US. We are also member of the DARWIN collaboration, which includes all XENON institutions and a number of other institutions.

National: Besides our close collaboration with other groups at Nikhef, we are deeply embedded in GRAPPA, a Research Priority Area in Astroparticle Physics at the University of Amsterdam.

Grants and Awards

- → FOM Program: 2012 – PI: M.P. Decowski
- → Co-recipients of the Snellius Prize 2015: A.P. Colijn & F.Linde]
- → Co-recipient of the 2015 Breakthrough Prize: M.P. Decowski
- → eScience Grant: 2015 – PI: C. Tunnell

Key Publications

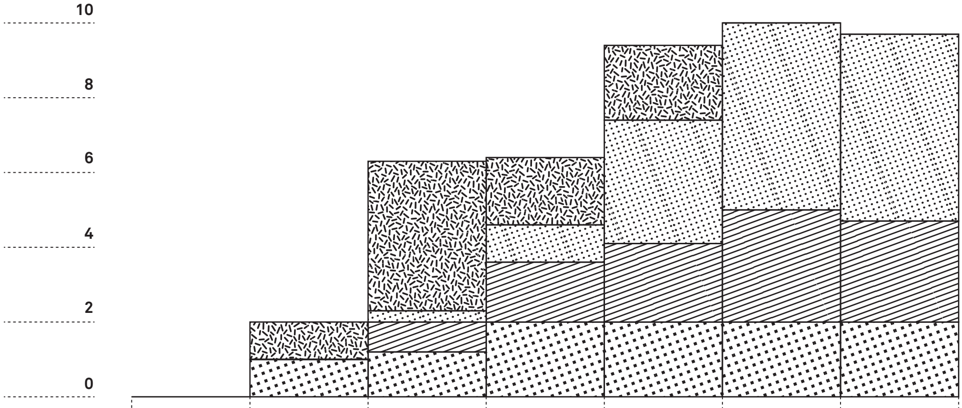
1 E. Aprile et al. (XENON Collaboration), *"Dark Matter Results from 225 Live Days of XENON100 Data"*, Phys. Rev. Lett. 109 (2012) 181301. [1300 cits]
2 E. Aprile et al. (XENON Collaboration), *"Limits on Spin-dependent WIMP-nucleon Cross Sections from 225 Live Days of XENON100 Data"*, Phys. Rev. Lett. 111 (2013) 021301. [263 cits]
3 E. Aprile et al. (XENON Collaboration), *"Physics Reach of the XENON1T Dark Matter Experiment"*, JCAP 1604 (2016) no. 04, 027. [140 cits]
4 E. Aprile et al. (XENON Collaboration), *"Low-mass dark matter search using ionization signals in XENON100"*, Phys. Rev. D94 (2016) no. 9, 092001. [16 cits]
5 E. Hogenbirk et al., *"Commissioning of a dual-phase xenon TPC at Nikhef"*, Nucl. Instrum. Meth. A840, 87 (2016).

Side Activity: Neutrino Physics with KamLAND(-Zen)

One of us (M.P. Decowski) has continued to be active in the KamLAND(-Zen) neutrino experiment during 2011-2016. KamLAND(-Zen) is a 1 kton liquid scintillator detector in the Kamioka mine in Japan. After a successful run as a neutrino oscillation detector in 2002-2011, the KamLAND detector was modified to contain ~380 kg of 90% enriched ^{136}Xe at the center of the detector in 2011. Although the experiment initially suffered from complications due to the Fukushima-I nuclear fallout, it was able to set the world's best limits on neutrinoless double beta decay, published in PRL[4], in 2016 (M.P. Decowski was on the writing team for this paper). He remains involved in reviewing analyses, writing KamLAND(-Zen) papers and taking shifts. Nikhef hosted the biannual KamLAND(-Zen) collaboration meeting in Amsterdam in September 2016.

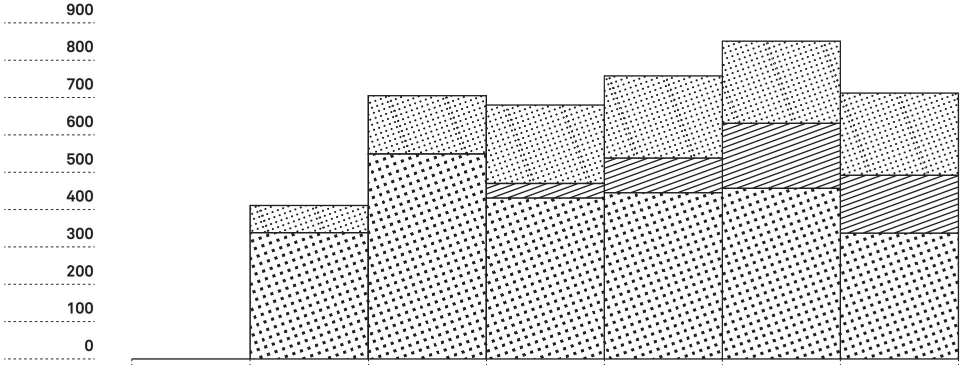
[4] A. Gando et al. (KamLAND-Zen Collaboration), "Search for Majorana Neutrinos near the Inverted Hierarchy Region with KamLAND-Zen", Phys. Rev. Lett. 117 (2016) no.8, 082503.

FIGURE 21 **Dark Matter manpower** (in fte)



	'10	'11	'12	'13	'14	'15	'16
Technical staff		1,0	4,0	1,8	2,0	0,0	0,0
PhD students		0,0	0,3	1,0	3,3	5,0	5,0
Postdocs		0,0	0,8	1,6	2,1	3,0	2,7
Staff		1,0	1,2	2,0	2,0	2,0	2,0

FIGURE 22 **Dark Matter budget** (in k€)



	'10	'11	'12	'13	'14	'15	'16
Universities		73	156	210	220	220	220
FOM-university groups		0	0	39	93	174	155
FOM-Nikhef		338	549	431	445	457	337

THEORY

Programme Organization
Programme leader:
- prof. dr. E. Laenen

Deputy programme leader:
- prof. dr. R. Fleischer

University partners:
- VU, RU, RUG

The theory groups located at VU, RU and at the Van Swinderen Institute at RUG (since 2016) are members of the Nikhef theory group as well. The VU group is located at, and fully integrated with Nikhef Amsterdam.

The Amsterdam group pursues its own research programme, and interacts and collaborates with the experimental groups at Nikhef. It also acts as a national center for theoretical particle phenomenology in the Netherlands, through joint grants and monthly workshop meetings.
Due to the move of P. Mulders and the remarkable funding success, the group in Amsterdam has grown to 10 staff members and about 15 postdocs and 15 PhD students, as well as numerous Master and Bachelor students, constituting a lively and stimulating environment for research, which offers also many opportunities for collaboration.

Nijmegen theorists W. Beenakker and R. Kleiss have been members for the full duration; they are moreover active in the FOM programme Higgs as Probe and Portal. In 2013 R. Loll, F. Saueressig and J. Ambjorn joined: their research is focussed on quantum gravity.

Theorists of the Van Swinderen Institute (VSI) in Groningen became members in 2016. D. Boer, E. Pallante and R. Timmermans collaborate with Nikhef through the Higgs FOM programme, D. Roest through the cosmology programme.

Research Goals
- To describe and understand the properties of subatomic particles and of fundamental interactions
- To study theoretical models, such as the Standard Model, for predicting and describing new and existing experimental or

observational results, mostly in the framework of quantum field theory
- To develop analytical and computational tools for these studies

Research Highlights
- The theory group has been extraordinarily successful in obtaining external funding, being awarded many grants for both senior staff, and junior scientists. This has led it to grow to well over 40 members in Amsterdam alone, producing over 60 papers in 2016.
- Joining of theorists from Nijmegen working on quantum gravity, and of the Van Swinderen Institute. This further strengthened the central role that the theory group plays in Dutch theoretical particle physics landscape, for instance through the monthly Theory Center meetings.
- Important research results were obtained, such as the calculation of the N3LO Higgs production cross section, the development of new observables and methods in B-physics and QCD, and many results in cosmology, dark matter, gravity and string theory.
- FORM version 4 was published, including major new functionalities, enabling calculations to one loop order more than hitherto.

Research Activities
The Nikhef theoretical activities can be subdivided into several research themes that are listed below.

String theory and gravity
- B. Schellekens summarized the state of affairs in the string theory landscape and the multiverse as well as the anthropic arguments that inevitably come up in this context, in a Review of Modern Physics paper. He also investigated how the Standard Model can result from string and brane configurations.
- B. De Wit and his group worked on many aspects of supergravity in the review period, and on black hole thermodynamics. Particularly noteworthy are the identification of a clear connection between effective string actions and topological strings, and the development of new methods to determine actions for higher-dimensional supergravities.

Cosmology, dark matter, gravitational waves

→ M. Postma, together with a student and postdoc, performed the first full calculation of quantum corrections to Higgs inflation without making ad-hoc assumptions. She also examined, together with collaborators from Leiden, the viability of sgoldstino inflation.

→ J.W. van Holten and his PhD students analyzed the motion of spinning bodies in curved spacetime and derived conditions for the innermost stable orbit around a black hole. Significant progress was also made in modelling inspiral dynamics for black hole mergers.

→ K. Petraki and collaborators addressed possibly self-interacting, asymmetric dark matter, and wrote a well-cited review on this issue. K. Petraki also demonstrated the importance of bound-state effects on the phenomenology of interacting dark matter, which has led to significant international interest.

B-physics and CP violation

→ R. Fleischer and two of his PhD students proposed a new observable, the effective lifetime, for the search of New Physics using the rare decay $B^0_s \to \mu^+\mu^-$ in a joint paper with members of the LHCb group, published in Physical Review Letters. Moreover, subtleties in the interpretation of the $B^0_s \to \mu^+\mu$ branching ratio measurement were pointed out, receiving a lot of attention in the community. A pioneering first measurement of the effective lifetime of $B^0_s \to \mu^+\mu^-$ has very recently been performed by the LHCb collaboration. Also detailed CP violation studies of penguin effects in the decays $B^0_d \to J/\psi$ Ks and $B^0_s \to J/\psi\ \phi$ with a PhD student were done, leading to a roadmap for controlling these in the LHCb upgrade era. Indeed, LHCb is implementing the corresponding analyses.

→ A plot of a paper with G. Ricciardi (Univ. Naples) and PhD student R. Knegjens on the decays $B^0_{\{s,d\}} \to J/\psi\ f_0(980)$ was chosen for the cover of the corresponding issue of the European Physical Journal C. An invited Annual Review of Nuclear and Particle Science article was written by R. Fleischer and collaborators.

QCD predictions, methods and tools

- P. Mulders and his students analysed entanglement for azimuthal asymmetries in Drell-Yan and found difficulties with factorization of transverse momentum dependent (TMD) parton distribution functions in hadronic scattering, pointing out that they can be addressed through a careful study of Wilson lines. In other work, together with D. Boer and others, he showed how to study linear polarization of gluons inside a (unpolarised) nucleons emphasizing its possible importance at 'small x' (with postdocs Zhou, Petreska)
- A novel way to compute imaginary parts of eikonal diagrams was developed by E. Laenen and collaborators, leading to a Physical Review Letters cover. With other students and collaborators, he developed a formalism for organizing next-to-soft logarithms, discovering a surprisingly predictive pattern based on a novel factorization formula. In a study with a student and a collaborator, one-loop matrix elements were consistently introduced into the antenna-based parton shower programme VINCIA.
- Postdoc F. Herzog and collaborators computed, in a series of papers, the N3LO Higgs production cross section, a landmark result.
- W. Waalewijn and collaborators found new ways to help distinguish quark from gluon jets, using parton showers and resummation techniques. He also examined other aspects of jet physics, such as internal fragmentation and substructure. In an interesting cross-over project, he showed how to use Feynman diagrams for gravitational lensing.
- Postdocs J. Gaunt, T. Kasemets studied issues related to factorization in high energy scattering processes including also multi-parton processes. For this the role of transverse momenta of partons is considered as well as the use of soft collinear effective theory.
- J. Rojo and collaborators performed a precision determination of the gluon PDF at small values of the momentum fraction, exploiting the information contained in charm production at LHCb using the NNPDF global analysis methodology. This determination has important implications for ultra-high energy astrophysics experiments such as accurate predictions for signal and background events of high energy neutrinos at KM3NeT and IceCube.

Heavy ion physics

- P. Mulders and D. Boer have explored the extent to which the gluon TMD can be determined in a future Electron-Ion Collider.
- D. Boer and E. Laenen are part of a COST network (2016) for the theory of heavy-ion collisions.

Beyond the Standard Model

- The resummation of threshold logarithms for squark-gluino production was extended to NNLL accuracy by W. Beenakker, E. Laenen and collaborators, and released as public code NNLLFast.
- Postdoc L. Zeune together with collaborators performed a thorough parameter scan of the MSSM taking into account the Higgs data, and assessed the viability of interpreting the Higgs signal as being either the light or heavy CP-even MSSM Higgs.
- W. Beenakker and E. Laenen are part of a COST network (2016) for BSM physics.

Collaboration with experimental groups at Nikhef

Members of the theory group had many fruitful interactions with the Nikhef experimental groups. R. Fleischer collaborated closely with the LHCb group, with shared PhD students and joint papers. E. Laenen collaborated with the ATLAS group on top quark physics, through shared PhD and Master students. T. Kasemets interacted with ATLAS PhD students in the area of multiparton processes. A close interaction on modelling black hole mergers existed between J.W. van Holten and the Virgo group, sharing two PhD students. He also shared two PhD students with the HiSparc cosmic ray group. The theory group (R. Fleischer) has initiated half-day "Theory Meets Experiment" mini-workshops, addressing topics such as flavour physics, axions, sphalerons and BSM physics in an informal setting. The arrival of J. Rojo in 2016, working on NNPDF, will further expand interactions with ATLAS, LHCb, KM3NeT.

During the review period important public computer programs were (co-)written by theory group members, which are listed below. We list mainly the authors associated with Nikhef.

- FORM version 4 *[J. Vermaseren, J. Kuipers, T. Ueda, J. Vollinga]*, a general computer algebra program.
- MadGraph 5 *[M. Herquet, P. Artoisenet et al]*, automatic cross section and Monte Carlo generation.
- Golem 95C *[T. Reiter et al]*, automatic loop integrations.
- MadSpin *[P. Artoisenet, R. Rietkerk et al]*, for implementing spin correlations.
- FORCER *[B. Ruijl, T. Ueda, J. Vermaseren]*, four-loop propagator corrections, including automatic code generation
- Axodraw v2 *[J. Vermaseren et al]*, for high-quality drawing of Feynman diagrams
- NNPDF *[J. Rojo, V. Bertone, N. Hartland et al]*, parton distribution functions determined in a Neural Network approach.
- (N)NLLFast *[W. Beenakker, E. Laenen, et al]*, computes threshold-resummed squark-gluino cross sections.
- VINCIA *[L. Hartgring, E. Laenen, M. Ritzmann, P. Skands]*, an antenna-based parton shower.
- APFEL *[J. Rojo]* a program that implements PDF evolution up to NNLO in QCD and NLO in QED and that provides on-line graphical plotting functionalities for PDFs and related collider observables.

We also mention the interesting visual map of the arXiv at paperscape.org, created by former theory group postdoc D. George and PhD student R. Knegjens, while at Nikhef.

National and international collaboration

In the past decade, the theory group has played a central role in making Dutch theoretical particle physics, especially phenomenology, more coherent and interactive, creating a larger community for fostering new ideas and new collaborations. This is done in part through formal associations of groups at the VUA, RU and VSI with Nikhef, but more concretely through the national FOM programmes and their mechanisms. A very important instrument in this regard is the monthly Theory Center day-long meeting, mostly held at Nikhef, featuring two general talks, a student-only talk, joint discussion of experimental results, and much unstructured time for informal collaboration. Often experimenters join in as well.

Twice a year Nikhef hosts the National Seminar of Theoretical High Energy Physics, intended for all theorists working in this area. This event features four plenary talks, organized by D. Boer (until 2012), R. Fleischer (since 2012) together with theorists at other Universities. This meeting is an excellent occasion to learn about new developments in adjacent specialties, and have further fruitful informal contacts.

The theory group has a well-run theory seminar organized by postdocs, as well as a bi-weekly journal club. Another important element for a vibrant research environment regard are visitors. During the review period there were many short-term visitors. There were extended visits by R. Godbole (Bangalore, 2011), C. Quigg (Fermilab, 2011), L. Magnea (Turin, 2013), S. Frixione (CERN/Genova, 2014), H. Dreiner (Bonn, 2016), Y. Kurihara (KEK, 2016), A. Mukherjee (IIT Bombay, 2014, 2015 and 2016), Y. Zhou (Shandong U, 2015). Fleischer co-organizes the Nikhef Colloquium.

Theory group members take part in many small-scale, informal collaborations, too numerous to mention here, with colleagues from all over the world. Two international collaboration mechanisms for PhD students we mention explicitly:

- → EU training networks LHCPhenoNet and HiggsTools. An interesting aspect of these has been the secondment of PhD students to industrial partners such as Wolfram (Illinois) and Shell (Rijswijk, Netherlands). Students found this to be very valuable and interesting.
- → Theory PhD students can spend up to two months in theory groups abroad on Nikhef funds, if there is mutual interest. Students in the group have visited TU Munich, Stanford University and the University of Edinburgh, leading to new collaborations, papers, and even postdoc offers. Conversely, the theory group hosted PhD students from Edinburgh, Aachen and Muenster.

Grants and Awards

- → ERC Advanced Grant:
  - → 2011 – B. De Wit
  - → 2012 – J. Vermaseren
  - → 2012 – P. Mulders
- → Marie Curie Individual Fellowships:
  - → 2012 – W. Waalewijn
  - → 2012 – P. Artoisenet
  - → 2013 – D. Butter
- → ERC Starting Grant:
  - → 2015 – W. Waalewijn
  - → 2016 – J. Rojo (bringing remaining ERC-SG with him to Nikhef)
- → NWO VIDI Grant:
  - → 2014 – S. Murthy (declined)
  - → 2015 – K. Petraki
- → NWO VENI Grant:
  - → 2011 – N. Banerjee
  - → 2015 – J. de Vries
  - → 2015 – L. Zeune
- → European Networks:
  - → 2011 – LHCPhenoNet, PI: E. Laenen
  - → 2014 – HiggsTools, PI: E. Laenen
- → FOM Projectruimte:
  - → 2011 – De Wit
  - → 2012 – P. Mulders
  - → 2012 – M. Postma
  - → 2013 – F. Saueressig
  - → 2013 – R. Loll & Ambjorn
  - → 2016 – E. Laenen & M. Vreeswijk (ATLAS)
  - → 2016 – R. Fleischer & M. Merk (LHCb)
- → FOM Program Funding:
  - → 2014 – PI: R. Loll
  - → 2015 – with M. Postma
  - → 2015 – PI: E. Laenen
- → Elected APS Fellow: 2011 – P. Mulders
- → Elected to Royal Academy of Sciences: 2015 – R. Loll
- → Knight in the Order of the Netherlands Lion: 2014 – B. De Wit
- → Netherlands' Scientific Delegate to the CERN Council: E. Laenen

Key publications

1 C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger, *"Higgs Boson Gluon-Fusion Production in QCD at Three Loops"*, Phys. Rev. Lett. 114 (2015) 212001.

2 K. De Bruyn, R. Fleischer, R. Knegjens, P. Koppenburg, M. Merk, A. Pellegrino and N. Tuning, *"Probing New Physics via the $B^0_s \rightarrow \mu^+\mu^-$ Effective Lifetime,"*, Phys. Rev. Lett. 109 (2012) 041801.

3 A.N. Schellekens, *"Life at the Interface of Particle Physics and String Theory"*, Rev. Mod. Phys. 85 (2013) no.4, 1491-1540.

4 B. von Harling and K. Petraki, *"Bound-state formation for thermal relic dark matter and unitarity"*, JCAP 1412 (2014) 033, arXiv:1407.7874

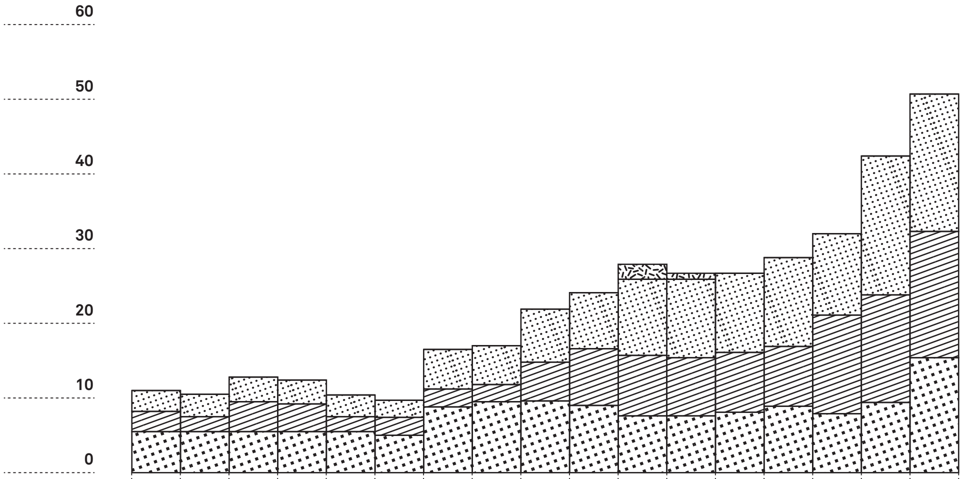
5 M.G.A. Buffing, P.J. Mulders, *"Entanglement for azimuthal asymmetries in the Drell-Yan process"*, Phys. Rev. Lett. 112 (2014) no.9, 092002

6 M. Procura, W. J. Waalewijn, and L. Zeune, *"Resummation of Double-Differential Cross Sections and Fully-Unintegrated Parton Distribution Functions"*, JHEP 1502 (2015) 117.

7 H. Gies, B. Knorr, S. Lippoldt and F. Saueressig, *"Gravitational Two-Loop Counterterm Is Asymptotically Safe"*, Phys.Rev.Lett. 11 (2016) no. 21, 211302.

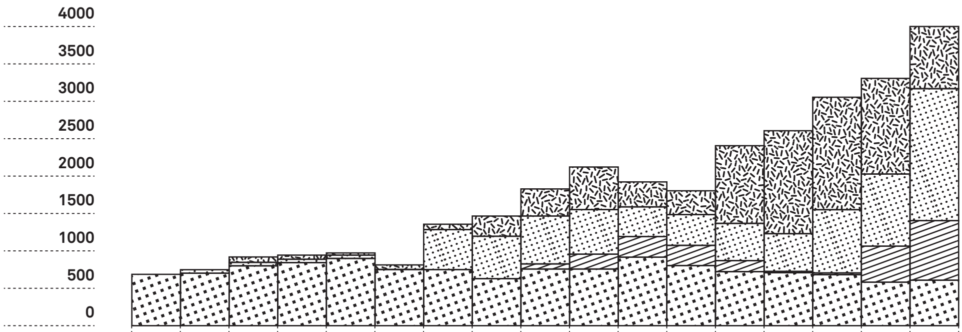
8 R. Gauld and J.Rojo, *"Precision determination of the small-x gluon PDF from charm production at LHCb"*, Phys. Rev. Lett. 118 (2017) 072001.

FIGURE 23 **Theory manpower** (in fte)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical staff	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,0	0,8	0,0	0,0	0,0	0,0	0,0
PhD students	2,8	3,0	3,3	3,2	2,9	2,3	5,3	5,2	7,1	7,5	10,2	10,5	10,6	11,9	10,9	18,6	18,4
Postdocs	2,7	2,0	4,0	3,7	2,0	2,4	2,4	2,3	5,2	7,6	8,1	7,8	8,0	8,0	13,2	14,4	16,9
Staff	5,5	5,5	5,5	5,5	5,5	5,0	8,8	9,5	9,6	9,0	7,6	7,6	8,1	8,9	7,9	9,4	15,4

FIGURE 24 **Theory budget** (in k€)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects			70	54	28	59	69	262	350	552	323	309	1006	1334	1457	1239	805
Universities		45	45	43	43	0	518	549	621	577	384	398	482	488	819	934	1710
FOM-university groups									66	192	268	261	143	17	23	466	771
FOM-Nikhef	665	680	775	817	871	728	727	609	734	734	887	779	700	686	660	564	589

DETECTOR R&D

Programme Organisation

Programme Leader:

- dr. N.A. van Bakel

Research Goals

Answering the biggest mysteries in physics requires pioneering experiments. New instrumentation ideas need to be initiated and developed long before they can be implemented in Nikhef's scientific experiment: from proof of principle to scientific instrumentation, applying latest technologies, and with an open mind towards industrial applications.

Dynamics of the DR&D program:

- Basic instrumentation R&D with (future) Nikhef experimental programmes
- Explore new technologies in synergy with Nikhef engineering departments
- Knowledge transfer with high-tech research institutes, Dutch top-sector & industry

The group has been active in the following R&D areas:

- LCTPC: now called LEPCOL
- Medipix
- SENSEIS: Readout of ASICs for MEMS accelerometers
- MEMBRane
- Industry: with TATA Steel, Medical (with Mammo and Flexray), Amsterdam Scientific Instruments
- TALENT, INFIERI

Research Highlights

- We presented the most precise gaseous pixel detector to date for measuring the position of individual ionisation electrons at the IEEE-NSS 2014 conference. This leads to improved angular (2.5 degrees) and position (in-plane 10 μm) resolutions on fitted tracks. It finds applications in self-triggering and on-chip pattern recognition for use in, e.g., the ATLAS L1 trigger or Proton Radiography.

- Together with the Nikhef Dark Matter group, we constructed XAMS – a xenon facility in Amsterdam– now operational to investigate detector technologies and xenon medium properties in a dual-phase xenon time projection chamber (TPC).
- Work together with the Nikhef Gravitational Physics group led to alignment and monitoring systems for Virgo's optical test masses, a programme to develop ultra- sensitive accelerometers for future Gravitational Wave detectors.
- Hosting of the TIPP 2014 conference: *the* Technology and Instrumentation in Particle Physics 2014 (www.tipp2014.nl) conference has been hosted by Nikhef in *De Beurs van Berlage,* downtown Amsterdam from June 2–6. It is new series of cross-disciplinary conferences on detector and instrumentation falls under the auspices of the International Union of Pure and Applied Physics (IUPAP) with 450 attendees brought together world experts from the scientific and industrial communities to discuss current work and to initiate partnerships that may lead to transformational new technologies.
- The award of grants like ERC grant to H. van der Graaf in 2012 was very important for the DR&D group and allowed us to start a new field of instrumentation research.

Research Activities

Semi-conductor detectors

The granularity of particle detectors is ever increasing and hence many detectors adopt pixel architectures. The Nikhef R&D group and Electronics Department are actively involved in the design and characterisation of pixel sensors and readout chips.

Readout ASICs

To develop state-of-the-art pixel electronics, the DR&D group is closely involved in the Medipix collaboration since 1998. Nikhef started developing timing circuitry for pixelated particle detectors about ten years ago. The Timepix3 chip, which became available in the second half of 2013, is the latest member of a successful pixel chip family. This radiation hard ASIC was developed together with CERN PH/ESE. The timing resolution (1.56 ns) has been improved compared to the previous version by almost a factor of ten and this gives a large improvement in the z-resolution for our GridPix detectors discussed below. Besides the arrival time of the hit, each pixel also measures the signal charge by determining the time where the signal is over threshold. Another major improvement in Timepix-3 is that the zero-suppression of the data is now done on chip. This gives an enormous reduction in data volume and thereby an increased track readout rate compared to the non-zero-suppressed frame-based readout as used in the previous version. To cope with the full data-stream of about 6 Gbit/s an FPGA based readout system (SPIDR) has been developed. This system controls the Timepix3 chip, packs the output data and sends it over a 10 Gbit/s ethernet network to the data acquisition.

Many features of the Timepix-3 have been adopted for the pixel chip called VeloPix which is developed for the vertex detector upgrade (VELO) of the LHCb experiment. This chip became available in 2016 and has an eight times higher hit rate capability and features an output bandwidth of almost 20 Gbit/s. This enormous bandwidth required the development of a new high speed serialiser.

Semiconductor Sensors

Driven by the demand for large area detectors, we work on seamless tessellation of multiple modules. This requires sensors with a minimum amount of dead area at the edge. For this, edge effects must be understood and avoided or mitigated. Both slim-edge and active-edge sensors have been studied at Nikhef. Slim-edge structures are manufactured by dicing the sensor closer to the pixel matrix. This is not the case for active-edge sensors. There, the electric field is terminated at the edge by extending the back electrode to the edge sidewalls, for example by doping the edges after dicing.

A Silicon telescope for detector characterization

Within the scope of the LHCb VELO upgrade project, a particle tracking telescope has been constructed based on the Timepix3 ASIC. The telescope consists of eight sensor planes read out with the SPIDR readout system, which has been developed at Nikhef, and is (partially) funded by the AIDA FP7 project. In the second half of 2014, the telescope was successfully used at the 180 GeV mixed hadron beam at SPS to characterise the first prototype silicon sensors of the VELO upgrade. Thanks to the excellent pointing resolution of less than 2 μm, high resolution time tagging, and the enormous track rate capabilities (10 Mtrack/s), detailed studies of the sensors, and the behaviour of the corresponding readout ASICs were possible. Besides the VELO, also other LHCb upgrade groups and the Nikhef *GridPix* development benefitted from the availability of the telescope.

Medical Instrumentation

A number of medical imaging projects are ongoing in the Nikhef detector R&D group. The main focus is X-ray imaging and in particular spectral X-ray computed tomography (CT). With hybrid pixel detectors based on the Medipix3 chip it is possible to both count the number of photons, as well as separate these detected photons in a number of energy bins. This is achieved with a single detector while industry uses multiple detectors or multiple irradiations. As opposed to the mainstream use of energy information after CT reconstruction, a statistical approach is used to include energy information directly in the reconstruction algorithm. In this way, beam hardening artefacts can be removed and particular elements like contrast agents identified. . It is also believed that new detectors will improve other issues, such as signal-to-noise ratio and dose reduction. Hence, spectral CT is considered to be the future of X-ray imaging.

The aim of an ERC Proof-of-Concept grant on mammography developments, together with Utrecht University, is to apply Medipix3-based detectors to enhance the contrast between calcifications and tumours. At the Utrecht Medical Centre a standard X-ray system is used for patient diagnosis. The research goal is to improve this diagnostic tool, together with local radiologists, by adapting our Medipix3 system such that realistic phantoms can be measured yielding additional information for physicians.

Gaseous pixel detectors

The GridPix detector is a fine-granularity pixel chip with a gas amplification grid on top that is able to record the time of arrival of the incoming signal. Thanks to the small pitch of the pixel cells ($55 \times 55\ \mu m^2$), the detector collects the individual electrons that are liberated in the gas volume by a traversing charged particles. This allows a 3-D track reconstruction of the ionising radiation. The x-y position is given by the pixel matrix and the z position is derived from the time of arrival of the drifting ionisation charge.

An effort is ongoing towards mass production of GridPix devices since 2010. The goal is to complete all post-processing on full-size 200 mm Timepix wafers to ensure the production of numerous spark-proof GridPix detectors of high quality and reliability. In collaboration with the MESA+ institute at the University of Twente, IZM Fraunhofer Institute in Berlin, and Bonn University, numerous GridPix batches on wafer scale have been fabricated. Major advances in the production process and quality control have been demonstrated and provided new ideas to further improve the technology.

This kind of tracking detector, collecting all information that can be deduced from the ionization trail of a charged particle in gas, has a wide range of applications like, e.g., a time projection chamber at an experiment at the International Linear Collider (ILC).

Ultra-fast photon detectors

Harry van der Graaf proposed in his ERC-ARG 'MEMBrane', a photon detector based on Micro Electro Mechanical Systems (MEMS) technology aiming at picosecond temporal resolution. The difference between a traditional photo multiplier tube (PMT) and this novel detector is in the nature of their dynodes. A PMT has reflective dynodes, whereas this research is developing transmission dynodes that will be stacked on top of each other. This simplifies the configuration and reduces the size to the scale of our pixel chips (55 µm). As a consequence, the time response is improved and the sensitivity to magnetic fields is decreased. The main challenge is to fabricate ultra-thin transmission dynodes with sufficient Secondary Electron Yield (SEY) at low primary electron energy, *i.e*. a yield of four electrons at 500 eV. Various transmission dynodes and test samples have been realized and the electron yields have been measured and calculated by means of GEANT-4 Monte Carlo simulations, applying special low-energy extensions. The secondary electron yield of several samples has been measured and the maximum yields 5.5.

Nikhef contributions

Although many of the research projects in the Nikhef R&D group are geared towards fundamental development of novel detector technologies, the group also participates in the development of detectors for specific experiments. There are ongoing collaborations with the Nikhef Advanced Virgo, LHCb, KM3NeT, Dark Matter and ATLAS groups.

National and International collaborations

Together with Philips, we are participating with two students in the INFIERI Initial Training Network on cutting edge technology in telecommunications, photonics and electronics; and the number of students with a Master project in detector development is increasing.

Silicon is widely used as radiation detection medium and became a mature technology but has limited absorption capacity, especially for higher energetic X-rays used in medical applications. Research with Philips in the INFIERI training network tries to overcome limitation by edge-on illumination of Silicon sensors, which increases the effective absorption depth for X-rays. This project also develops new methods of signal processing per pixel in the read-out chip, to ensure maximum use of the dose applied to a patient.

As already mentioned above, the Nikhef R&D group actively collaborates with various Nikhef experimental groups.

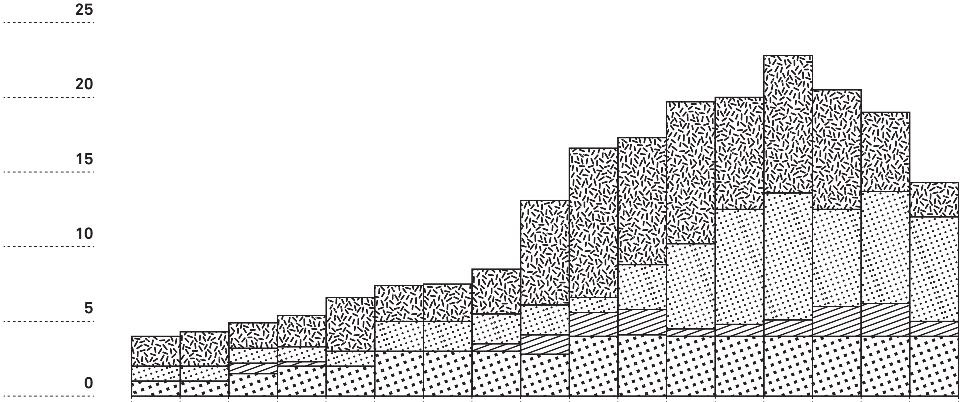
Grants and Awards

- Jan Kluyver Prize: 2014 – E. Schioppa
- Co-recipients of the 2016 Breakthrough Prize: N. van Bakel, M. van Beuzekom
- ERC Advanced Grant: 2012 – H. van der Graaf
- High Tech Systems and Materials (HTSM) Project Grant: 2015 - SENSEIS
- STW Open Technology: 2011 – J. Visser
- STW Valorisation Grant: 2011 – N. van Bakel
- AIDA Detector R&D: 2011 – E. Koffeman
- INFIERI: 2012 – N. Hessey
- TALENT: 2012 – N. Hessey
- Patents:
  - *Photon detector with high time resolution and high spatial resolution,* Inventor: H. van der Graaf (2012).
  - *A method to measure the specific resistivity of thin layer material without the need for a second surface contact,* Inventors: H. van der Graaf, F. Hartjes (2015)

Key Publications

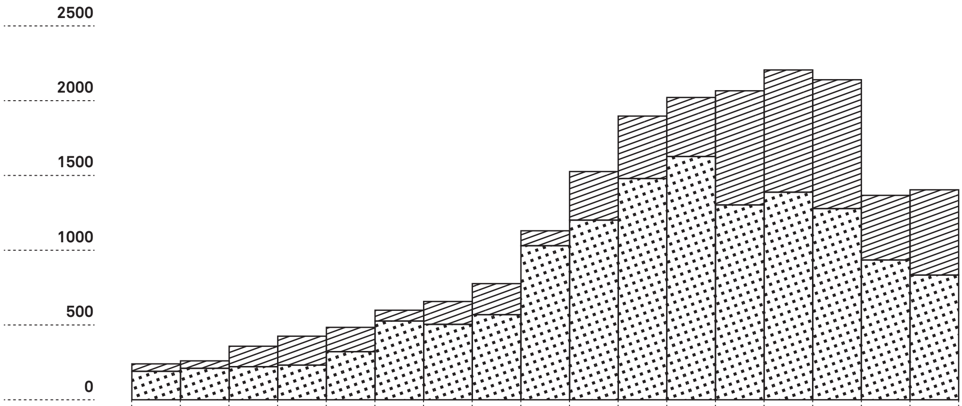
1. S. Tsigaridas, N. van Bakel, Y. Bilevych, V. Gromov, F. Hartjes, N.P. Hessey, P. de Jong and R. Kluit, *"Precision tracking with a single gaseous pixel detector",* Nucl. Instrum. Meth. A 795 (2015) 309.
2. Y. Bilevych et al., *"Porential applications of electron emission membranes in medicine",* Nucl. Instrum. Meth. A 809 (2016) 117.
3. E.J. Schioppa, M. Idarraga, M. van Beuzenkom, J. Visser, E. Koffeman, *"Study of Charge Diffusion in a Silicon Detector using an energy sensitive pixel readout chip",* IEEE Trans. Nucl. Sci., 62 (2015) 2349.
4. J. Melai et al., *"An integrated Micromegas UV-photon detector",* Nucl. Instrum. Meth. A 633 (2011) S194.

FIGURE 25 **Detector R&D manpower** (in fte)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical support	2,0	2,3	1,7	2,1	3,6	2,4	2,5	3,0	7,0	10,0	8,5	9,5	7,5	9,2	8,0	5,3	2,3
PhD students	1,0	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	1,0	3,0	5,7	7,7	8,5	6,5	7,5	7,0
Postdocs			0,7	0,3				0,5	1,3	1,6	1,7	0,5	0,8	1,1	2,0	2,2	1,0
Staff	1,0	1,0	1,5	2,0	2,0	3,0	3,0	3,0	2,8	4,0	4,1	4,0	4,0	4,0	4,0	4,0	4,0

FIGURE 26 **Detector R&D budget** (in k€)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects	50	50	137	193	163	72	153	208	100	325	418	395	763	817	862	432	570
FOM-Nikhef	190	210	221	232	321	527	504	569	1030	1201	1479	1626	1303	1388	1278	935	834

PHYSICS DATA PROCESSING (ADVANCED COMPUTING FOR RESEARCH)

Programme Organization
Programme Leader:
→ dr. J.A. Templon

This Nikhef programme is not associated with a specific NWO programme, but is funded out of the mission budget. The activity started in 2000. Since 2001 approximately 75% of the funding for this activity comes from external sources such as EU-Framework programmes or national (Dutch) subsidies for e-infrastructure deployment and research. Funding for the LHC Tier-1 Computing Center is assured until 2019, via an NWO "Roadmap" Grant for LHC upgrades.

Research Goals
The high-energy physics research effort requires very-large-scale computing infrastructures to accomplish its research goals. Other branches of science are increasingly joining the large-infrastructure club as their research data grows in volume. The PDP group carries out research targeted at solving the computing challenges presented by our local research, research carried out within our national and international collaborations, and when appropriate, by our scientific counterparts in other research domains. Carrying out such research entails actually doing it; experience here and elsewhere shows that reasoning and intuition seldom anticipate all the major hurdles encountered when making significant advances in ICT research infrastructures. This aspect distinguishes the research at Nikhef from academic research on distributed computing being done in a university setting.

Research Activities

The group's research activities can be grouped in the following three categories:

- Advanced Computing Technologies (ACT) projects aim to define the composition and architecture of our research infrastructures and hardware on a 2 to 5 year horizon.
- Applied Advanced Computing (AAC) projects target increased physics reach via research on new algorithms, systems, and software infrastructure; the viability, validity and utility is ultimately tested by application to Nikhef research.
- Infrastructure for Collaboration (I4C) comprises both infrastructure security (local and worldwide) and collaboration infrastructure. The collaboration infrastructure work has its roots in LHC style of global collaboration, but is applicable to many science domains.
- A final activity straddles the line between applied research and facility operations: Research Infrastructures (RI) operated by the group are used by Nikhef physicists (Stoomboot), our experiment colleagues (LHC Tier-1, VIRGO, XENON) and by other sciences (Dutch National eInfrastructure). The research component of this activity is strongly linked to ACT, an example question is, "what developments are needed in and for the Tier-1 infrastructure in order to deal with network traffic approaching the terabit/s scale, as expected in the HL-LHC era?"

Research Infrastructures

The two major research infrastructures we operate are firstly the second-largest node in the Dutch National eInfrastructure (DNI), the Nikhef Data Processing Facility (NDPF). The other is the "Stoomboot" cluster (and associated high-throughput storage) used for local computation, simulation, and analysis. Despite limited operations manpower, both facilities have been upgraded several times over the period, following the increasing needs of our own users, and of other researchers making use of the DNI.

The NDPF was the vehicle for major contributions of computing resources from Nikhef to the ATLAS, LHCb, ALICE, Pierre Auger, and VIRGO experiments, and for DNI users, leading to 97% utilization over the period.

TABLE 21 **Scale increase of the local research infrastructures over the period**

Facility	Resource	2011	2016
Stoomboot	CPU	256 cores	750 cores
Stoomboot	Disk	150 TB	700 TB
NDPF	CPU	40 kHS06 (3600 cores)	86 kHS06 (5800 cores)
NDPF	Disk	1.6 PB	2.5 PB
NDPF	Network	200 Gb/s	850 Gb/s

The large increase in data storage for Stoomboot was enabled by moving from the GlusterFS file system to dCache. Developments were done in close collaboration with the dCache team at DESY in Hamburg.

Advanced Computing Technologies

Grid technology was unique at the start of the period; the rest of the world has embraced distributed computing in the meantime, and there is much to be gained from basing our facility on open standard technologies; the amount of support and documentation is vastly greater, and it further opens our facility to other researchers using the DNI. These users have little interest in "the Grid", but are often keenly interested in "the cloud".
The vision is to collect all our compute facilities under a single virtualisation-management framework, on top of which we can instantiate "WLCG" for the Tier-1, "Stoomboot" for local users, and "NL Cloud" for non-HEP DNI users, moving computing power between segments according to demand.

The HL-LHC will have data volumes a couple orders of magnitude larger than those of today. Research was conducted (in collaboration with major networking hardware vendors such as Juniper) to enable these data flows. At the end of the period, underlying infrastructure in NDPF was capable of 48 Tb/s, with certain components already dimensioned for 100 Tb/s. Related work was started (and continues, again in collaboration with vendors) to define storage architectures for the HL-LHC era; this is related to the problem of increasing disk size (and experimental data volume) in the absence of accompanying advances in single-spindle data read speeds. Finally, during the period, R&D was conducted associated with usage of accelerators such as GPGUs and Xeon Phi cards.

Applied Advanced Computing

Knowledge from our RI and ACT was applied to building a machine specially designed to execute large-scale FORM calculations. G. Raven carried out research on re-engineering the LHCb trigger code for performance on modern CPU architectures; the net gain achieved was 40%. The LHCb trigger team applied results from this research to ultimately win a factor 2 in performance.

A pilot project on Machine Learning was carried out. It has not yet been possible to expand the scope of this activity, as it is quite hard to find external funding for this, and the demand from within Nikhef (at that time) was insufficient to justify use of internal funds.

Infrastructure for Collaboration

Working together in a way that is trustworthy, protected, and at the same time globally inclusive, requires very diverse elements of the infrastructure to come together. The Infrastructure for Collaboration (I4C) R&D activity looks for scalable security mechanisms that work across administrative domains, across national boundaries, and across research disciplines. The initial focus on granting access to site-local compute resources and on the establishment of trusted identity for the grid platform has significantly broadened: we have exploited opportunities offered by the maturing of general-purpose “R&E” identity federations in order to grant access to grid and other e-Infrastructure services by means of the user’s home organization credentials. Our expertise in ‘translating’ security credentials and our practical approach of working production-quality prototypes has enabled for example the new “Cauth.eu” service that has been taken up by e-Infrastructures (EGI) as well as domain infrastructures such as the ELIXIR ESFRI infrastructure for life sciences. Through our participation in the EC co-supported projects EGI-INSPIRE, EMI, IGE, EGI-ENGAGE, and AARC, alongside our commitments to the success of federation for both the Dutch National e-Infrastructure, within the WLCG community, the impact of the work is ensured. Impact was further enhanced by participating in REFEDS (the global R&E federation operator policy group), in the GEANT Trusted Certificate Service TCS policy management authority, as well as by continued leadership in the Interoperable Global Trust Federation.

The development of software that supports collaboration remains an important element of the infrastructure work at Nikhef. Besides continued support for globally deployed software such as LCMAPS and gLExec (in use in EGI, WLCG, and the US-based Open Science Grid), the group has added new products to support science gateways (web-portal based research workflows) in a secure manner, and added support for differentiated assurance that enables more use cases to be supported on both grid and cloud based infrastructures.

Yet granting access to legitimate users has inevitably to take into account the continuous threats to the integrity and availability of the infrastructure. The recent years have seen significant increase in both intensity as well as complexity of cybersecurity threats. With Nikhef leadership the EGI-CSIRT was formally audited and accredited by TF-CSIRT, the European coordination body for security incident response spanning both academia and industry. Through pro-active training and more re-active advanced forensics, the I4C operational security team handled threats from both the inside as well as from external actors.

Nikhef Contributions

Nikhef is a partner in the Dutch National eInfrastructure (DNI). Together with SURFsara (the lead partner in the DNI), we provide a Tier-1 computing center for the LHC experiments ATLAS, LHCb, and ALICE; a Tier-0 mirror for the XENON experiment; and provide significant computing power for the VIRGO collaboration. As a DNI node, we provide cycles for a diverse set of sciences outside of HEP. Finally, group members have executed several short-term advanced-technology projects as contribution to collaborations in which Nikhef participates; a particular example is design of a major upgrade for the internal and external network infrastructure for the XENON experiment.

Nikhef hosted the CHEP (Computing in High-Energy Physics), the most important conference in our field, in 2013 in the Amsterdam Beurs van Berlage.

Memberships

- K. Bos: GridKa Overview Board (2011); Helmholtz-Alliance for Physics at the Terascale International Advisory Board (2011)
- D. Groep: Conference Chair, 20th International Conference on Computing in High Energy Physics (CHEP 2013); CHEP International advisory committee 2014-present; European Policy Management Authority for Grid Authentication in e-Science (EUGridPMA) (chair 2011-present); International Grid Trust Federation (chair, 2011-present); International Symposium on Grids and Clouds, programme committee (2014-present); Open Grid Forum - Standards Function Security Area (director, 2011); Open Grid Forum CA - OPS working group (co-chair 2012-present); TERENA Technical Committee (TTC) of the Geant Association (2014-present).
- J. Templon: Worldwide LHC Computing Grid (WLCG) Management Board (2011-2013); WLCG Overview Board (2014 - present); Netherlands eScience Center, eScience Integrator (2012-present); CHEP International Advisory Committee 2014-2015;

National and International Collaborations

Nationally, Nikhef is an active participant in (and advocate for) the Dutch National e-Infrastructure and has close ties with the Netherlands eScience Center. Internationally we are a core partner in the Worldwide LHC Computing Grid, the European Grid Infrastructure, and a member of the EU-T0 collaboration.

Grants and Awards

- H2020: 2015 – EGI Engage, D. Groep
- H2020: 2015 – AARC, D. Groep

Key Publications

1 D. L. Groep (ed.) and D. Bonacorsi (ed.), *"Proceedings, 20th International Conference on Computing in High Energy and Nuclear Physics (CHEP 2013)"*, J. Phys. Conf. Ser. 513 (2014).

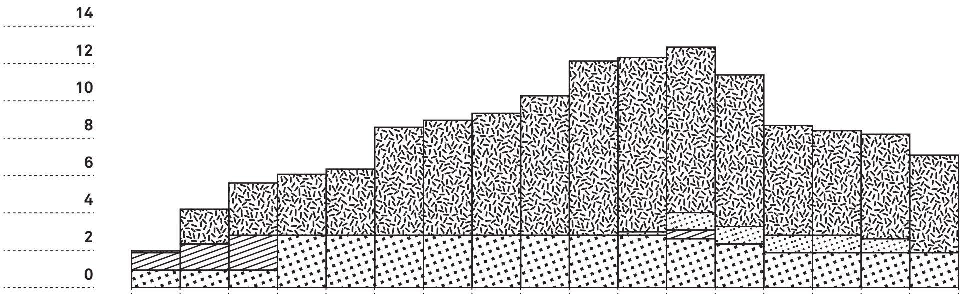
2 D. Kelsey, *"A Trust Framework for Security Collaboration among Infrastructures"*, PoS ISGC 2013 (2013) 011.

3 J. A. Templon, C. Acosta-Silva, J. F. Molina, A. C. Forti, A. P. Yzquierdo and R. Starink, *"Scheduling multicore workload on shared multipurpose clusters"*, J. Phys. Conf. Ser. 664 (2015) no. 5, 052038.

4 J. A. Templon and J. Bot, *"The Dutch National e-Infrastructure"*, PoS ISGC 2016 (2016) 020.

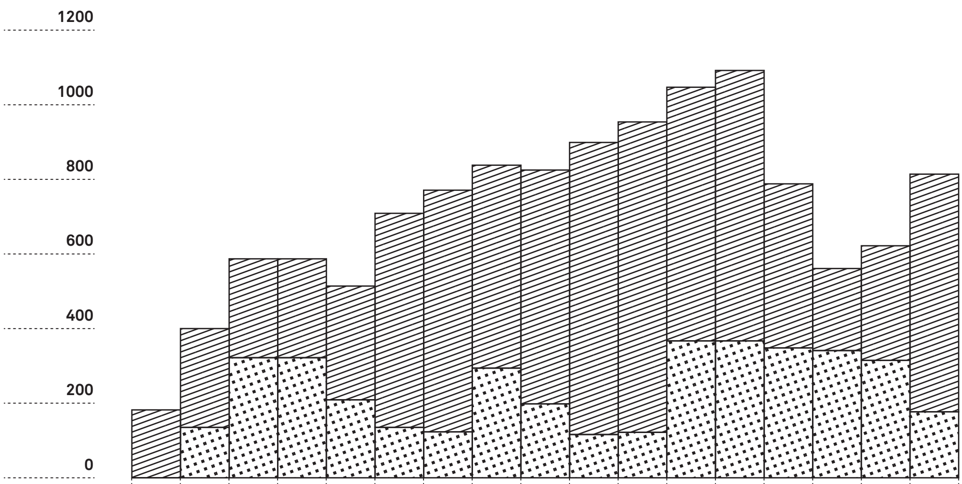
5 D. Remenska et al. [LHCb Collaboration], *"Optimization of large scale HEP data analysis in LHCb"*, J. Phys. Conf. Ser. 331 (2011) 072060.

FIGURE 27 Physics data processing manpower (in fte)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Technical support	0,1	2,0	3,0	3,5	3,8	6,2	6,6	7,0	8,0	10,0	10,0	9,5	8,7	6,3	6,0	6,0	5,6
PhD students											0,2	1,0	1,0	1,0	1,0	0,8	
Postdocs	1,0	1,5	2,0									0,5					
Staff	1,0	1,0	1,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	2,8	2,5	2,0	2,0	2,0	2,0

FIGURE 28 Physics data processing budget (in k€)



	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Projects	182	265	265	265	305	574	648	544	627	783	832	680	725	440	220	307	637
FOM-Nikhef	0	135	322	322	209	135	123	294	198	116	122	367	367	348	341	315	177

\ RELEVANCE TO SOCIETY

ACTIVITIES IN OUTREACH AND COMMUNICATIONS

Website/social media

As an important platform for all its target audiences, Nikhef continuously improves its website. In 2016 a completely modernized website was launched with new design, new navigation and a new content management system, in order to meet the evolving needs of all target groups. These include increased interest in photo and video material, and demand for tailor-made approaches to fit the different target groups.

The period of 2011-2016 has also seen an enormous increase in Nikhef's social media activities. From first steps in 2011, this has led by the end of 2016 to more than 1,200 followers on Twitter, nearly 800 followers on Facebook, 3,252 followers on LinkedIn, and to the start of new activities on Instagram.

Guided tours at Nikhef and at CERN

Since the enthusiasm for fundamental research is 'par excellence' conveyed in personal contact and first-hand experience, Nikhef organises and supports countless guided tours for very diverse groups both at Nikhef in Amsterdam as well as at other laboratories, whose experiments Nikhef participates in, notably at CERN. Especially during the long shutdowns at CERN, when it was possible to visit the underground LHC tunnel and the experiments, Nikhef invited many science and technology decision makers and representatives from industry and economy for unique visits. State Secretary (Education, Culture and Science) Sander Dekker was welcomed at CERN. Dedicated visits were also organised for delegations of NWO, FOM, Executive Boards of partner universities, the Business Leaders NL network and many more.

Special events

Nikhef also organised or took part in a couple of special events. To name a few examples, in 2014 Nikhef celebrated CERN's 60th anniversary with a festive symposium with guest of honour CERN's Director General Rolf Heuer. Nikhef scientists featured as interviewees in theatre performances of Jan van den Berg. Pictures of Nikhef's research projects can be found in the "Steps of Science", a work of art by Nienke Korthof in which lenticular tiles in the stone paving at Amsterdam Science Park form a walk of fame.

Open day

Every year in October, Nikhef welcomes hundreds of people at the institute's Open Day. Visitors can attend short lectures, follow demonstrations, and talk to Nikhef scientists and engineers from all of Nikhef's research groups and technical departments. Children can take part in special workshops and a particle treasure hunt. The Open Day is organized together with the other institutes, universities and companies at Amsterdam Science Park as part of the 'Weekend van de Wetenschap' (Weekend of Science).

Outreach talks

Nikhef scientists together give on average about 70 outreach talks per year for the general public all across the Netherlands. This is at a variety of occasions, such as science cafes and symposia, science associations and museums. Nikhef scientists appeared for example at KIJK Live! (organised by the Dutch science magazine KIJK), Bessensap (annual event organised by NWO and VWN where "science meets the press"), Paradisolezingen, KNAW symposia, the Gala of Science, also at the University of the Netherlands and Lowlands University, to name just a few. For a full account, we refer to the Nikhef Annual Reports.

Exhibits and exhibitions

Nikhef has continued to operate and display a number of dedicated exhibits for outreach purposes developed in earlier years. In the central hall of the main Nikhef building, one can find a cloud and a spark chamber visualizing cosmic rays, moreover mock-ups and large prints of some of the experiments Nikhef participates in. Furthermore, a new exhibit, an 'arche cosmique', has been developed and built to demonstrate the spatial distribution of cosmic rays. One large version of this exhibit is displayed at Nikhef, another smaller version is available to travel to outreach activities at other locations. Four mobile spark chambers built by Nikhef can be borrowed by schools or universities or brought along to outreach events. The large spark chamber installation developed and built by Nikhef and donated to the NEMO Science Museum in Amsterdam has been improved and reinstalled in the permanent exhibition at NEMO. In 2014, Nikhef brought the CERN exhibition 'LHC time tunnel' to the Netherlands. For a few weeks, visitors at NEMO were interactively taken into the world of subatomic physics by using motion sensors and projectors. With their body motion, visitors could simulate the effect of the Higgs field or make protons collide.

Media coverage

Nikhef's research has attracted a considerable amount of media coverage between 2011 and 2016, both online as well as in print, on radio and TV. Especially the two big scientific discoveries of the Higgs boson in 2012 and gravitational waves in 2016 made it into all national and regional newspapers, into monthly (science) magazines, and into many radio and TV programmes. Among the highlights were mentions on the front pages of national newspapers, and interviews with Nikhef scientists in RTL Nieuws and NOS-Journaal on national television. Another highlight was surely the broadcast of the documentary "Higgs: into the heart of the imagination" with Stan Bentvelsen and other Nikhef researchers on the evening of the Higgs discovery which for this occasion came in a new edition including a number of extra scenes. On the evening that the first detection of gravitational waves was announced, Nikhef researchers Jo van den Brand, Chris Van Den Broeck and Gijs Nelemans were invited to the most popular Dutch talk show 'De Wereld Draait Door' which has more than a million viewers.

But also other topics related to Nikhef's research are regularly mentioned in the media, such as the latest news on the operation of the LHC and the upgrading and opening of new astroparticle physics experiments and new results from the increasing amounts of data recorded with all these experiment. Furthermore articles about outreach and education activities of Nikhef, appointments of Nikhef researchers, examples of knowledge transfer, or interviews, columns and blogs by Nikhef scientists are published. To give an indication of media coverage, for example the number of articles in print media on Nikhef-related research and topics reached up to several hundred in the years of the two big discoveries, namely 2012 and 2016.

Activities for the media

Nikhef issued on average up to ten full press releases per year, often in collaboration with other institutes and universities, sent out to an extensive list of Dutch journalists. Furthermore Nikhef informed the media by means of on average around 50 shorter news items per year published on the Nikhef website and distributed via social media.

On an individual basis, Nikhef organised visits for journalists to the dark matter experiment XENON1T at the Gran Sasso laboratory and the gravitational wave experiment Virgo, both in Italy. In 2013, Nikhef in collaboration with the CERN press office invited nine Dutch journalists to

CERN for a National Media Visit. The two-day programme consisted of visits to the underground LHC tunnel and experiments, a general introductory talk and ample time for one-on-one interviews with Nikhef scientists.

For the announcements of both the discovery of the Higgs boson and of gravitational waves, dedicated press conferences were organised at Nikhef which were attended by dozens of journalists including film crews of several Dutch TV national news channels. For these national media events, Nikhef scientists gave talks sharing these breaking news stories, and parts of the simultaneous press conferences held at CERN for Higgs and at Virgo and LIGO for gravitational waves were webcast at Nikhef. Subsequently, journalists got ample opportunity to ask questions and interview Nikhef scientists involved in these scientific breakthroughs.

NIKHEF KNOWLEDGE AND TECHNOLOGY TRANSFER: SPIN-OFF COMPANIES, AWARDS AND PATENTS

Amsterdam Scientific Instruments Holding (ASIH)

The potential of hybrid silicon pixel detectors for tracking applications in High Energy Physics (HEP) has been successfully demonstrated over the last two decades. Essential in these developments have been the design of advanced CMOS readout ASICs and their integration with semi-conductor sensors. Nikhef has been involved from the start in the Medipix collaboration to transfer HEP pixel detector technology towards other applications such as Medical and Analytical X-ray imaging. This has resulted in a close collaboration between the Medipix-collaboration and the Dutch company PANalytical.

Former Nikhef R&D department member Jan Visschers started the Medipix effort at Nikhef in 1999 and in 2009 he won a prize for the business proposal with the highest potential at the - Valorisation workshop of the Dutch Technology Foundation STW. His wish was to start a high-tech start-up at Amsterdam Science Park Amsterdam to produce high quality semi-conductor radiation detectors. After Jan Visschers retirement this idea was picked up by Niels van Bakel and Jan Visser from the Detector R&D group, together with Hans Roeland Poolman, from 1&12 IP (and also a former PhD from Nikhef). In July 2011 Amsterdam Scientific Instruments BV was officially founded as a high-tech spin-out from Nikhef.

In the course of 2011 – 2016 the company (now ASIH) managed to grow to about 10 employees and to reach a turnover of more than 1 M€. The prospects for increasing turnover are good. However, the company's balance suffers from quite a large amount of financial claims generating a capital cost (interest), that cannot be easily accommodated. Currently solutions are explored to clear the balance and involving a 'fresh' investor, who will also contribute to the management of the company.

Sensiflex

On 1September 2011 Sensiflex BV has been officially established. This event concluded a two year period of discussions between Nikhef management, Sensiflex management and the prospective shareholders on the agreements to be drafted, including a shareholder agreement and a license agreement between Nikhef and Sensiflex BV.

Sensiflex supplies the Rasnik monitoring system for the civil engineering industry. Engineering company Fugro, Sensiflex's launching customer, has played a major role in attracting the first few orders.
In particular tunnels and bridges are monitored in three dimensions (plus time) with an accuracy up to 10 nanometre with relatively simple components.

In the second year of its operation the CEO of Sensiflex decided to leave the company. The remaining management team did not succeed in finding an alternative. Also discussions with another civil engineering firm to have them incorporate Sensiflex equipment in their services did not deliver concrete results. In recent years activities at Sensiflex has therefore been limited with occasional purchase orders and a turnover of several tens of thousands per years, just enough to cover the costs of continuing this activity.

Innoseis

The company Innoseis has been established mid 2013 by Nikhef's Gravitational Physics programme leader Jo van den Brand and his former PhD student Mark Beker. Innoseis aims to market technologies spinning out of Nikhef gravitational-wave instrumentation activities. The company has been subcontracted in the framework of the ‘TremorNet’ project, a cooperation contract agreed between VU, Nikhef and Shell, on the delivery of a proof-of-concept low power wireless seismic sensor network, successfully delivered early 2014. Two follow-up agreements with Shell have been concluded, one entailing the successful delivery and deployment of 100 ‘blind’ seismic nodes and another on the delivery of five sensors using Long Range wireless communication technology.

Moreover, Innoseis was awarded orders for calibration of seismic sensors in their unique vibration-free environment. The turnover of Innoseis has grown to 0,56 M€ in 2016. Currently Innoseis is in intensive discussions with investors to raise funds enabling the company to increase its activities in R&D and sales and marketing.

FOM (P2IP) does not own shares in this company. The IP position has been arranged through a license agreement between Innoseis and Nikhef and VU University, concluded successfully per 1 October 2014. This covers the licensing of the Nikhef/VU patent on MEMS based sensors using mechanically preloaded springs.

NoZAP

In 2013 another startup company has been established, NoZAP, aiming at developing live streaming television on demand. A Nikhef engineer with expertise in grid development and operations (in particular the networking aspects) was involved in this company. After one and a half years of operations, the company decided to end its activities, due to the unclear business perspective.

TABLE 22 **Valorisation awards and prizes**

Activity	Grant	amount
Amsterdam Scientific Instruments	STW valorisation grant	200 k€
Innoseis	Valorisation grant VU	100 k€
[Innoseis] - Mark Beker	FOM valorisation thesis prize	5 k€
[Innoseis] - Jo van den Brand	FOM valorisation prize	250 k€

TABLE 23 **Patents**

	Description	Year	Owner	Status	Licensed (y/n)
RasCLIC	'Werkwijze en inrichting voor het meten van geringe vervormingen of verplaatsingen van objecten' (alignment)	2007	Nikhef	Granted NL	Y
CO_2 cooling	Compact cooling system and cooling method for accurate temperature control.	2011	Nikhef + CERN	Granted PCT, US	N (under negotiation)
Tipsy	Photon detector with high time resolution and high spatial resolution.	2012	Nikhef	Granted NL	N
TDMA	Location based protocol and time slot schedule for a wireless mesh network.	2013	Nikhef + VU	Granted NL Pending: PCT, US	N (under negotiation)
MEMS accelerometer	MEMS sensor structure comprising mechanically preloaded suspension springs	2014	Nikhef + VU	Granted NL Pending: PCT, US	Y
Specific Resistivity	A method to measure the specific resistivity of thin layer material without the need for a second surface contact.	2015	Nikhef	Granted NL	N
Displacement sensor	Relates to methods and systems for accurately and/or reliably determining displacements	2016	Nikhef	Pending	N
Micro HV	Miniature high voltage source	2016	Nikhef + TU Delft	Pending	N

TECHNICAL DEPARTMENTS, FACILITIES AND SUPPORT

ELECTRONICS TECHNOLOGY

Projects in Electronics Technology (ET) department

In the past years some significant activities were executed: LHCb "Scintillating fiber detector"- SciFi (Upgrade of the outer tracker), LHCb VELO VeloPix IC development, ATLAS DAQ system FELIX-for the New Small Wheels, Virgo phase camera & linear alignment system, KM3NeT optical network, power and readout electronics, and a generic readout platform (SPIDR) for MediPix/TimePix (v1,2 &3) pixel chips.
Since upgrades and/or new projects require a long time for defining requirements and then design, prototyping, validation and production, most of the mentioned activities are still ongoing.

For LHCb SciFi (commissioning 2020), the electronics is almost ready for pre-production. It consists of FPGA based electronics in a radiation harsh environment, with very strict cooling requirements. The complexity of the design lies in the integration with mechanics, other subsystems, and the complex software environment of the Data Acquisition system, that is developed elsewhere in parallel.

The VeloPix chip is now under test and the results are being reviewed. If required, an optimized (final) design could be produced 2nd half 2018. The 5Gbps serializer output, and configuration logic is designed in the ET.

In 2017 the final prototype of the ATLAS FELIX board is expected, and firmware and software development will continue until commissioning (2020). The ET plays a major role in FPGA firmware development and coordination.

For KM3Net are optical sensor modules (DOM's) in production, and some first detection units (DU's, each with 18 DOM's) developed and under test. The optical network is designed and partly in use. Firmware and software developments for the system (in the detector and on shore-DAQ) are still ongoing, and preparations are being made for expanding the KM3NeT system for phase 2.

The Virgo experiment officially started in 2017, so all systems are in place, but optimizations the phase camera are still ongoing (FPGA firmware). Next to this, the ET delivered analogue electronics for alignment monitoring of the laser beams and controls for the Cryogenic Links.

The SPIDR Pixelchip readout system is in use by the Nikhef R&D group, is partially transferred to ASI (Nikhef spin-off) and has been adapted to the VeloPix for fast tests on the high speed data output of the IC.

New expertise/infrastructure:

In the past 5 years we experienced an increase in speed of data transmission over cables and on PCB's. To cope with the requirements for the design of these systems, more advanced modelling-, simulation- and measurement tools are needed. The ET invested in an advanced simulation tool (Keysight ADS) for design verification (PCB's with components & ASIC's) for high frequencies (RF/GHz) electromagnetic wave simulations. In addition a Vector Network Analyzer was acquired for detailed measurements (and verification) of complex and application specific cables (networks), such that this information can be added to the simulation environment. And finally, we invested in an advanced high speed (33GHz) real-time oscilloscope for verification of the complete system. This enables us to do accurate in-situ measurements, and verify this with equalization techniques for improving of the quality of receives signals (data). This has been applied with VeloPix design & test and the LHCb SciFi electronics.

The described tools came with increasing our skills and knowledge on the subject, but also in increasing our design strength on PCB design; high frequency, high density (small components, mm scale), FPGA's with > 1000 pins (BGA's) and adding 3D design capabilities for optimization of electronics in mechanical structures (EMI, cooling). On PCB level we invested in knowledge and methods for "Design for Manufacturability", to make sure that our designs can be produced and tested in a reliably by industrial companies.

Software design tools on PCB design, FPGA firmware development and simulation, IC design and verification (analogue as well as digital) bring us yearly new features and increased capabilities for developing new electronic circuits and systems. FPGA's evolved into "System On Chip" modules, that require complete design teams for several years to fully exploit all capabilities to "program" one single device, and it requires close interaction with software engineers. These techniques enables us to design the ATLAS DAQ FELIX system, KM3Net White Rabbit firmware, TimePix and VeloPix ASIC's (~300M transistors) with required test facilities, and the PMT-base IC's for Km3Net.

The focus is more in design with highly skilled engineers, and we now outsource most production activities.

Collaboration in design of electronics has increased significantly, tooling for this enables the engineers to work multi-site, worldwide, in parallel in collaborations on one single design, e.g. in IC's like VeloPix, or FPGA firmware for KM3NeT (as in software for embedded systems). This will grow further in the years to come. What is ramping up presently is the integration of mechanical and electrical (concurrent) design.

These activities require a close technological involvement of physics researchers (project leaders) in the engineering activities for the projects.

Projects on the horizon are further upgrades of detectors in LHC experiments (e.g. LHCb), implementation of new technologies in KM3NeT for phase2, a new generation of pixel detector IC's with very fast timing (~100ps time of arrival) measurements, extreme sensitive seismic sensor electronics for Gravitational Wave experiments, and generic DAQ systems for large experiments (LHC/ILC, KM3NeT, P. Auger, Einstein Telescope).

TABLE 24 **Projects**

Year	Experiment	Project/subject	Item
2008-2016		IC design: FEI4, RD53	IC development Inner tracker, serial data transfer circuits & library characterization IC for 65nm, prototype IC for rad-hard 5Gbps serializer in 65nm CMOS.
2008-now		SciFi electronics	System design & board-design of Masterboard (rad-tol. FPGA), initial Clusterboard, integration in DAQ system, FPGA firmware development and test system.
2008-now	KM3Net	Central Logic Board (in DOM)	Initial design, FPGA firmware development, timing system (White Rabbit) development and implementation, testing, coordination.
2010-2016	KM3Net	Optical Network	Design, demonstration, optical test bench, validation, coordination, component tests (e.g. high pressure), technical support for optical cabling, seafloor network, deployments etc.

CONTINUE →

Year	Experiment	Project/subject	Item
2010-2016	KM3Net	Power	Initial (CLB-) Powerboard design, 400V12V DC/DC convertor
2010-now	KM3Net	Photomultiplier's (PMT)	-PMT base PCB design with 2 Nikhef ASIC's -Circuit design for 3 PMT manufacturers, detailed PMT qualification, -Production (European tender) test setup, used for 15000 bases
2013		Octopus Board	Board in Digital Optical Module (DOM) to connect PMT's.
2011-2016	ALICE	ITS upgrade	-IC Contribution to pAlpide IC (CERN), reference & Temp sensor. -Research on applying serial power scheme (test IC)
2011-2012	R&D & Third party	R&D for seismic sensor readout	First electronics developed, design transferred to spin-off company. Featuring low power and low noise.
2011	Virgo	Linear alignment	Analog F-E electronics for 4 quadrant photo-diodes
2012-now	Virgo	Phase Camera	ADC & Digital data processing and networking (FPGA firmware development)
2011-2014	Virgo	CryoLink	Cryogenic link control system
2011-2014	Virgo	Bench Suspension	F-E electronics for LVDT monitoring and control + cabling.
2011-2013	ATLAS	DAQ: RobinNP	Intermediate DAQ system for ATLAS (FPGA firmware dev.)
2012-now	ATLAS	DAQ FELIX	Advanced DAQ system (FPGA firmware) high data throughput
2013	ATLAS	MuCtPi2Topo	Interface module between ATLAS Muon- and Trigger modules.
2013-2015	ATLAS	Rasnik	New frame-grabber hardware system (outsourced)
2011-now	LHCb	Velo Upgrade (VeloPix)	IC design of serial data output and configuration circuit of the VeloPix chip (Nikhef-CERN).
2012-now	All	Data transmission	Analysis on media (cables: electrical/optical) and circuits for data transmission and methods.

CONTINUE →

Year	Experiment	Project/subject	Item
2008-2014	R&D	TimePix3 IC	IC design (Nikhef-CERN) of a large pixelchip with fast Time Of Arrival time measurement per pixel.
2012-2016		SPIDR (Speedy PIxel Detector Readout)	Several variants of an advanced readout system for MediPix/TimePix pixel IC's with fast data readout. Also used for VeloPix test (20Gbps). Compact SPIDR design is transferred to spin-off company.
2015	XENON1T	Amplifier & support	R&D on PMT amplifier & local support for Lab tests
2014	Outreach	HiSparc II	Design, upgrade, production of HiSparc modules (ADC & FPGA & GPS)
2016	"	Muonlab III	Upgrade & production of Muonlab modules (ADC & FPGA)
2016	"	Steel tomography	Detector readout for Steel tomography (FPGA firmware dev.)
2015-now	CTA (for UvA)	Camera readout	FPGA firmware development for Cherenkov Telescope Array experiment, with White Rabbit timing support and PCB design.
Cont.	R&D	R&D	Support for Nikhef lab experiments with electronic circuits & controls. Further development of White Rabbit timing and calibration methods.
Cont	All	EMC	EMC qualification: measurements for Electromagnetic interference
Cont.	All	Education	Supervising internship projects for R&D on future applications. Guest Lectures at "Hogeschool Van Amsterdam", contributions to schools for PhD students.

MECHANICAL TECHNOLOGY

The main task of the Mechanical Technology department (MT) is to develop, design, and realize mechanical solutions for the mostly large, international projects that Nikhef participates in. The projects concern detectors that find their way deep underground, in the desert, or a few kilometres below sea level.

The variety of requirements results in a wide range of mechanical technologies applied: high precision manufacturing, assembly and diagnostics, light and stiff design, ultra-high vacuum, single and two-phase (CO_2) cooling, cryogenic techniques, special welding and gluing, wire-bonding, high-pressure systems, 3D measuring techniques, finite element analysis etc.

Most projects benefit more and more from additive manufacturing (3D printing) possibilities in metal, plastic and ceramics. For example, both the complex thin-walled titanium cooling structure and the surrounding foam isolation box of the readout box of the Scintillating Fiber detectors (SciFi) for LHCb are 3D printed.

The MT abundantly uses composite materials, that are both lightweight and stiff. This requires thorough material research, for example on the influence of heat and humidity on the stability of the material, in order to guarantee a certain precision. With the use of finite element analyses the characteristics of the designs can be predicted very accurately.

At the workshop the instrument makers have both conventional and modern, computer guided metal lathes and milling machines at their disposal. The department has invested in two new 5 axis CNC milling machines and one CNC lathe. One of them is in use for the manufacturing of the thin walled RF foil for the LHCb's vertex locator (VELO). With a coordinate measuring machine the shape and thickness of the RF foil is checked to the micron level.

TABLE 25 **Projects**

Experiment	Subsystem	Special technology applied
All:		Precision engineering, light and stiff construction, mathematical and computer modelling (FEM), precision machining and assembly, tooling, 3D-coordinate measuring, 3D printing, installation in situ,
ATLAS	Inner Detector	CO_2 cooling, composites
LHCb	Vertex locator	Vacuum, CO_2 cooling, composites
	Scintillating Fiber detector	Large structures, thermal insulation, cooling
ALICE	Inner tracker	Ultra-light and stiff construction, cooling

CONTINUE →

Experiment	Subsystem	Special technology applied
KM3NeT		High-pressure (500 bar), thermo-mechanical analyses, hydro-dynamics, extreme environment
Advanced Virgo		UH-vacuum, sensing & control
XENON 1T		Cryogenics
Pierre Auger Observatory		Extreme environment
Detector R&D		Wire-bonding

COMPUTER TECHNOLOGY

The mission of the Computer Technology (CT) department is to offer ICT support to the scientific research at Nikhef. The support is twofold: on the one hand, a reliable basic ICT infrastructure is provided to everyone in the institute. On the other hand, the application of flexible and innovative methods and techniques is used to facilitate the research.

The CT department consists of three groups that work on different activities: the system administration group manages the basic ICT infrastructure, the project support group provides software engineering support to experiments and the CT-PDP group contributes technical expertise to the Physics Data Processing (PDP) research programme. There is overlap in areas of expertise and interests between the groups, which results in exchanging knowledge between them. The responsibility for the housing services for the Amsterdam Internet Exchange and other internet exchanges, has been moved from the CT department to the new Nikhef Housing department.

The software engineering efforts have seen an increase in the development of embedded software and data acquisition systems for custom-built chips or devices using Field Programmable Gate-Arrays (FPGAs). This work is often done in close collaboration with the Electronics Technology (ET) department. Other software engineering projects were in the realm of controls systems for cooling systems, read-out and controls for an optical detector calibration system and various test and quality assurance setups. The group's expertise is now focused more on development of software and less on knowledge of measuring devices and industrial automation. Part of that expertise is present in the ET department, which may use external parties to complement the missing knowledge or capacity.

The local analysis compute and storage cluster, which is heavily used by Nikhef physicists and gives them a competitive advantage over research groups in other institutes, has been expanded with more computing cores and more storage space. To meet the higher demands in terms of performance and robustness, a different storage system based on dCache was introduced to replace the older GlusterFS system. The operational responsibility for the analysis facility has gradually shifted from the local system administration group to the CT-PDP group because the analysis facility is very similar to the Grid computing infrastructure in terms of systems and support questions from researchers. The PDP programme is described in more detail in its own dedicated chapter in this report.

The local infrastructure has seen various upgrades and improvements. A joint proposal for a collective infrastructure with neighbouring institutes AMOLF and CWI for the SURF Campus Challenge was awarded. As a result, the three institutes could obtain a common storage and network infrastructure. The hardware is housed at Nikhef, but is logically divided in separate parts for each institute, each of which can independently manage its own parts. The network connection to the rest of the world via SURFnet is also shared between the three neighbouring institutes. This connection was the first one among Dutch research institutes that was upgraded to 100 Gbps. Other improvements to the local infrastructure include the use of redundant hardware and fail-over services to increase the general availability of the services. To better protect the infrastructure against the continuous threats and attacks from the internet, but also the more widespread use of (private) mobile devices which cannot be considered as trusted devices, several systems were introduced to monitor and defend the infrastructure's integrity.

In the next years, the local infrastructure will be modernized. The internal network, which has organically grown over the past 20 years, needs to be reorganized to ensure its reliability, security and maintainability. In a world where outsourcing and the use of cloud services are common place, Nikhef will keep its local ICT staff and expertise. The diversity in the demands of users and projects, and Nikhef's informal culture, all benefit from the personal contact and frequently tailored solutions, instead of a one-size-fits-all infrastructure and corresponding service level. However, that doesn't mean that all services will continue to be hosted or managed by the local ICT group, and certainly not that new services will be developed by the group. Instead, the CT department will compare commercially available alternatives to local solutions when introducing new services or renewing existing services, to find optimal solutions for the demands by the users or projects while efficiently using the department's resources and manpower.

TABLE 26 **Projects**

Experiment	Projects
ATLAS	Development of embedded software for MROD, MuCTPiToTopo and Felix
ATLAS	Replacement of framegrabbers in the Rasnik alignment system
ATLAS	Slow controls system for the IBL cooling system, MDT controls
Detector R&D	Data-acquisition system for the Medipix and Timepix chips
KM3NeT	Development of embedded software for the Control and Logic Boards
KM3NeT	Simulations using GPU computing
Virgo	Control system for the cryolink systems
Wireless Sensor Networks	Design of embedded software, development of embedded software for sensor nodes

TECHNICAL FACILITIES

Nikhef avails over a wide variety of laboratory facilities. Apart from about ten 'general purpose' lab rooms for R&D and instrumentation, Nikhef has two clean room facilities.

The first is a large 170 m² class 10.000 cleanroom equivalent to the US FED STD 209E classification, which is equivalent to a class ISO 7 in the ISO 14644-1 scheme. This room is also temperature and humidity controlled and is constructed inside the big assembly hall of the mechanics workshop. It has been used for the construction of the external injection bench seismic attenuation system for Advanced Virgo. This is a single stage vibration isolation system that is operated in air. It uses passive mechanical resonators combined with anti-spring technology to provide isolation to seismic ground vibrations for gravitational waves detection. Currently it is being used for the production of the LHCb Scintillating Fiber Tracker modules.

The second clean area is the 'Silicon Alley', in which facilities are concentrated for handling and testing Si–chips and wafers as well as assembling detector systems. These facilities have been extensively used in the years 2000-2007 for assembling ZEUS, HERMES, ATLAS, LHCb and ALICE vertex modules. The foundations of this clean room area allow for extremely vibration–free positioning of any equipment. Since 2007 the area has been constantly used for prototyping efforts for the oncoming upgrade projects and work for companies. The facility is shared with PANalytical for their Medipix based detector production line and used by a number of other companies for wafer testing and prototype assembly work.

In 2016 one of the rooms has been refurbished to house a new Mitutoyo Crysta-Apex S 3D coordinate measuring system equipped with a contactless measurement system. This effort was carried out for the oncoming production of the detector ladders for the upgrade of the ALICE vertex detector modules. Per ultimo 2016 the most important facilities in this area are:

- → a 15 m^2 class 1000 clean room equivalent to the US FED STD 209E classification, which is equivalent to a class ISO 6 in the ISO 14644-1 scheme. This room contains one semi–automatic probe stations; a Süss PA300PS-MA to probe wafers up to 300mm. In this room is also located a FEI Phenom scanning electron microscopy and a Keithley 4200 semiconductor characterization system to perform measurements on semiconductor structures such as sensors;
- → a 30 m^2 class 10.000 room for detector module assembly and quality testing room in which a number of microscopes are located. A Zeiss Axioskop and a recent addition, the Zeiss Axio Zoom.V16 for high contrast imaging over a large focal distance with motorised Z and motorised X/Y stages achieving a maximum magnification of 180 and a resolution of 0.7 micron);

- a 35 m² class 10.000 temperature controlled clean room, in use for a large Wenzel LH 1210 3D measurement machine;
- a 30 m² class 10.000 room with the new Mitutoyo Crysta-Apex S 3D coordinate measuring system equipped with a contactless measurement system.
- a 40 m² assembly room where die–bonding and wire–bonding is performed. It houses a Hesse & Knipps BJ815 automatic wedge–wedge bonder, a manual wire-bonder as well as a TPT HB16 semi–automatic ball-wedge bonder for deep access configurations and small pitch down to 25 µm;
- a 30 m² class 10.000 clean room, containing a plasma cleaner to clean surfaces before die-bonding and wire-bonding. In this room there is also a sputter-coater to deposit gold to improve the imaging quality with the scanning electron microscope for non-conductive samples.
- a 30 m² room that doubles as a grey room for dicing and polishing of materials and as a dark room for extremely light sensitive detector module assembly quality testing room.

MANAGEMENT AND SUPPORT

Whilst the personnel office and the science communication department report directly to the Nikhef director, the support division is headed by the institute manager drs. A. van Rijn (deputy director). It consists of the secretariat (including reception desk), financial administration, facilities & datacenter, library, project management support and several staff members.

The main tasks of the secretariat (3.3 fte) are providing management support to the director, institute manager and programme leaders, handling travel requests of Nikhef personnel (over a thousand per year), managing agendas and supporting various boards and meetings. The reception desk (which is outsourced to a security company) handles all incoming general phone calls and monitors admittance to the Nikhef building, with special emphasis on checking admittance to Nikhef's datacenter facility.

The financial administration (3.8 fte) includes ordering goods, checking invoices, charging the appropriate budgets and project administration. The bookkeeping is done on an FOM wide system. The FA has much experience in handling transport (imports and exports) and in administrating VAT. The management of debtors (accounts receivable) is important (to illustrate: in 2016 Nikhef sent out almost 600 invoices, for a total amount of 8,4 M€). Externally acquired projects, often with varying rules regarding accountability, makes project administration an increasingly complex activity.

The department Facilities and Datacenter (~8 fte) is responsible for building maintenance and installations, such as clean room control, heating, cooling, power. While until about 2014 the responsibility for the datacenter operations resided under the Computing Technology department, since 2014 F&D has full responsibility for the Nikhef datacenter, with around 3 fte dedicated staff. The datacenter is certified to comply with standards set by the Amsterdam Internet Exchange (AMS-IX). Recently several measures have been taken to improve the energy efficiency of the datacenter, amongst which is using a thermal ground heat and cold exchange system. These measures have resulted in a relative reduction in energy consumption, expressed in a 'Power Usage Efficiency' factor (PUE) of 1,27 (i.e. only 27% electricity overhead due to cooling). For a 20 year old datacenter this can be called remarkable.

The safety department (1.6 fte), whose tasks include radiological and environmental safety, is responsible for safety and for proposing and monitoring all necessary measures to ensure healthy working conditions. Nikhef has a team of about 17 employees trained in first aid, fire extinguishing and accident prevention. Until 2017 Nikhef's safety officer has also served as the area coordinator for environmental affairs. Furthermore he also serves two other institutes (Amolf and ARC-NL) as safety officer.

Nikhef also provides the project manager (0.8 fte), who coordinates most of the area development within the Amsterdam Science Park on behalf of the land owner (NWO). The project manager is supported by the Nikhef-secretariat (0,5 fte). For these tasks Nikhef is financially compensated by NWO.

The library (0,6 fte) provides access to all relevant journals in the field. Following trends in electronic publication Nikhef management has since 2007 carried out a significant (50%) reduction in both the space and the personnel available for the library.

Two staff members (one taking over from the other in 2017) currently serve as Industrial Liaison Officer and also provide support to the Nikhef body for project planning and support. Another staff member (0,8 fte), physically embedded in the mechanical department, serves as project (production) manager for a large part of Nikhef's LHCb SciFi and KM3NeT technical commitments.

AWARDED GRANTS 2011 - 2016

FOM programmes	Title	Period	Budget (k€)	Partner
Decowski	The missing universe: what is the subatomic constituent of dark matter?	2013-2018	2.000	UvA
Loll	Quantum gravity and the search for quantum spacetime	2014-2018	1.200	RU
Linde et al.	LHC Physics	2014-2021	16.865	
Laenen	Higgs as a probe and portal	2015-2020	458	UvA
Achucarro	Observing the big bang: the quantum universe and its imprint on the sky	2015-2020	298	Lei
Van den Brand	First detection of gravitational waves with Advanced Virgo	2015-2020	1.046	VU
Hoekstra	Physics beyond the Standard Model with cold molecules: measuring the electric dipole moment of the electron in BaF	2017-2022	2.176	RuG

FOM projectruimte	Title	Period	Budget (k€)	Partner
Mischke	Charm content in jets	2011-2016	398	UU
Van den Broecke	Binary black holes as laboratories for fundamental physics	2011-2016	354	
P. de Jong	Mind the gap! Generalizing dark matter searches at the LHC.	2011-2016	264	
Igonkina	Search for tau decays to a muon and a photon to understand the lack of anti-matter in the universe	2012-2017	400	
Peitzmann	Thermal photon measurements in ALICE: probing the initial temperature of the quark-gluon plasma	2012-2017	394	UU
Mulders	Quantum chromodynamics at work in the Higgs sector	2012-2017	379	VU
Postma	Keeping track of time during inflation	2012-2017	385	
Van Eijk/ Bentvelsen	Splitting the Higgs: the connection to dark matter	2013-2017	400	
Filthaut/N. de Groot	Higgs as a portal to new physics	2013-2017	396	RU

CONTINUE →

FOM projectruimte	Title	Period	Budget (k€)	Partner
Mischke	A charming way to disentangle initial- and final-state effects at the LHC	2013-2017	270	UU
Ferrari	CP violation in the Higgs sector	2014-2018	396	
Saueressig	Black hole dynamics in asymptotically safe quantum gravity	2014-2018	398	RU
Van den Broecke	The discovery of gravitational waves with Advanced Virgo and LIGO	2015-2019	404	
Peitzmann	Solving the direct photon puzzle in heavy-ion reactions with direct photon interferometry	2016-2020	400	UU
Vreeswijk/ Laenen	Top spin	2016-2020	468	UvA
Merk/ Fleischer	Very rare beauty decays: a magnifying glass for quantum physics	2017-2021	504	

FOM-various	Title	Period	Budget (k€)	Partner
Linde	Tiling appointment (FOM/V)	2013-2017	326	
(Various)	FOM/V projects	2013-2017	425	RU
Van den Brand	Wireless seismic sensors (IPP)	2013-2017	256	VU
Bentvelsen	director's budget	2015-2019	500	
Van den Brand	Field studies with seismic and gravity-gradient sensor networks for gravitational waves physics and oil-and-gas exploration (TKI)	2015-2019	332	VU
Van den Brand	FOM Valorisation prize 2015	2016-2018	235	VU
Van den Brand	Studies with seismic sensors and long-range communication (TKI)	2016-2017	230	VU

NWO-Innovation Impuls	Title	Period	Budget (k€)	Partner
Igonkina	VIDI: Lepton flavour violation: the key towards a matter dominated universe	2011-2016	800	
Grelli	VENI: Research into a new state of matter	2012-2016	250	UU
Snellings	VICI: A new state of matter: The Quark Gluon Plasma	2012-2017	1.500	UU
Van Tilburg	VIDI: The high-precision frontier in beauty and charm decays	2013-2018	800	
Zeune	VENI: Towards realistic predictions for new physics searches at the LHC	2015-2018	249	
Grelli	VIDI: The hottest place in the Universe	2015-2019	800	UU
Mischke	VICI: Tomography of the Quark-Gluon Plasma - beauty quarks as a key probe	2015-2020	1.500	UU
De Vries	VENI: Heart of Darkness: how to unravel the nature of dark matter	2016-2019	222	
Petraki	VIDI: Deciphering the dark matter code	2016-2020	800	
Igonkina	VICI: Leptons that have created the world	2016-2021	1500	
Du Pree	VIDI: Higgs from Z to A	2017-2022	800	

NWO-investments	Title	Period	Budget (k€)	Partner
Van den Brand	Advanced Virgo - Probing the dynamics of spacetime	2012-2016	2.000	VU
Linde et al.	Dutch contributions to the detector upgrades of the LHC experiments at CERN	2014-2022	15.240	

NWO-various	Title	Period	Budget (k€)	Partner
De Groot	OSAF Research school for subatomic physics - NWO graduate programme	2010-2015	800	RU

Netherlands e-Science Center	Title	Period	Budget (k€)	Partner
Tunnell	Giving pandas a ROOT to chew on: Modern Big Data front and backends in the hunt for Dark Matter	2015-2016	50	
Samtleben	Real-time detection of neutrinos from the distant Universe	2015-2016	50	
Caron	iDark: The intelligent Dark Matter Survey	2016-2019	498	RU
Verkerke	Automated Parallel Calculation of Collaborative Statistical Models	2016-2019	491	

STW	Title	Period	Budget (k€)	Partner
Visser	New Detector Systems for Biomedical Imaging (together with Amolf)	2012-2016	300	
Van Bakel	SENSEIS: Silent sensors for stellar echo's and seismic surveys	2014-2019	495	UT

Third parties (NL)	Title	Period	Budget (k€)	Partner
Groep	EGI: Operational security	2013-2017	256	
Van den Brand	Shell: TremorNet	2013-2014	783	VU
Heubers	SURFnet: The 'Research Campus' (with Amolf and CWI)	2013-2014	100	
PDP group	SURFsara: Contribution to the national e-infrastructure	2013-2015	2.895	
P2IP	RVO: Knowledge-2-knowledge seminars rondom Single Quantum Imaging	2015-2016	84	
Van Eijk	Sectorplan Natuurkunde en Scheikunde: HiSparc	2014-2017	170	
Van den Brand	Shell: Next generation seismic equipment: Lora enabled seismic sensors	2016-2017	269	VU

European Commission	Title	Period	Budget (k€)	Partner
Koffeman/ Hessey	AIDA (detector R&D)	2011-2014	152	
Laenen	LHCPhenoNet	2011-2014	397	
Artoisenet	PROBE4TeVSCALE: Resolving short-distance physics mechanisms in hadron collisions at TeV scale energies	2012-2014	192	
Hessey	TALENT: Training for cAreer deveLopment in high-radiation ENvironment Technologies	2012-2015	545	
Van den Brand	ELiTES: ET-LCGT Interferometric Telescopes: Exchange of Scientists	2012-2017	32	VU
Waalewijn	PRECISIONJETS4LHC: Precise Predictions for Higgs and New Physics Signals with jets at the Large Hadron Collider	2013-2015	183	
Hessey/ Visser	INFIERI: INtelligent Fast Interconnected and Efficient Devices for Frontier Exploitation in Research and Industry	2013-2017	404	
Butter	HYPERGRAV: The last piece of the puzzle: Off-shell hypermultiplets in string theory and complex geometry	2014-2016	183	
Laenen	HIGGSTOOLS: The Higgs quest - exploring electroweak symmetry breaking at the LHC	2014-2017	251	
Groep	EGI Engage: Engaging the EGI Community towards an Open Science Commons	2015-2018	156	
Berge/ Heijboer	ASTERICS: Astronomy ESFRI and Research Infrastructure Cluster	2015-2018	364	UvA
Van Rijn	HNSciCloud: Helix Nebula – The Science Cloud	2016-2018	233	
Groep	AARC-2: Authentication and Authorisation for Research and Collaboration	2017-2019	236	
Groep	AENEAS: Advanced European Network of E-infrastructures for Astronomy with the SKA	2017-2019	67	
M. de Jong	KM3NeT 2.0 (Preparatory Phase, Nikhef is Coordinator)	2017-2019	786	

ERC	Title	Period	Budget (k€)	Partner
De Wit	AdG: Supersymmetry: a window to non-perturbative physics	2012-2016	1.910	UU
Mulders	AdG: Quantum Chromodynamics at Work	2013-2018	2.069	VU
Van der Graaf	AdG: MEMS-made Electron Emission Membranes	2013-2018	2.396	
Vermaseren	AdG: Solving High Energy Physics Equations using Monte Carlo Gaming Techniques - HEPGAME	2013-2018	1.739	
Mischke	ERC PoC: MammoMedipix: High Sensitivity Mammography with a new generation of silicon pixel sensors	2014-2015	149	UU
Kooijman	AdG: Chromium (PI: Jennifer Thomas, UCL, UK)	2016-2021	1.109	

MEMBERSHIPS OF (INTER)NATIONAL COMMUNITIES AND BOARDS

Academia Europaea / R. Loll (2015-2016)
Advances in High Energy Physics - Editorial Board / F. Filthaut (2015-2016)
Annual Conference on Large Hadron Collider Physics (LHCP) / P. Koppenburg (Program Committee) (2013-2016)
ASPERA / F. Linde (Governing Board) (2011-2012), H. Demonfaucon (joint secretariat) (2011-2012)
ASTERICS (Astronomy ESFRI Research Infrastructure Cluster) External Advisory Board / F. Linde (2015-2016)
Astroparticle Physics European Coordination (ApPEC) - Particle Astrophysics and Cosmology Theory (PACT) / J. van Holten (board member) (2013-2016)
Astroparticle Physics European Coordination (ApPEC) / P. Kooijman (peer review committee), F. Linde (steering committee) (2011-2014) J. van den Brand, F. Linde (chair) (2015-2016), S. Bentvelsen (2016)
Astroparticle Physics International Forum (APIF) / S. Bentvelsen (2016)
BEAUTY, Int. Conference on B-Physics at Hadron Machines – International Advisory Committee / R. Fleischer (co-chair) (2011-2016)
Big Grid – Directorate / F. Linde, A. van Rijn (2011-2012)
CERN Council / S. de Jong(2011-2014) (chair) (2015-2016)
CERN European Strategy Group / S. de Jong, F. Linde (2012-2014)
CKM workshop 2016 - Mumbai / P. Koppenburg (Program Advisory Committee) (2016)
Combinatorics, Physics and Their Interactions, Annales de Henri Poincaré l'Institut D (AIHPD / R. Loll (editor) (2015-2016)
Committee Dijkgraaf / S. de Jong (2013-2014)
Committee for Astroparticle Physics in the Netherlands (CAN) / J. van den Brand, C. van den Broeck (co-chair), P. Decowski, J.R. Hörandel (chair), D. Samtleben (Leiden), C. Timmermans(2015-2016)
Computer Algebra Nederland – Board / J. Vermaseren (2011-2016)
Dutch Research School for Theoretical Physics) / J.W. Van Holten (Education Committee) E. Laenen (Governance Board) (2011),W. Beenakker, F. Saueressig, P. Mulders (Educational Board) (2015-2016)
ECFA PG1 - steering group / S. Caron (ATLAS representative for SUSY and Exotics) (2015-2016)
e-Infrastructure Reflection Group (e-IRG) / A. van Rijn (Dutch delegate) (2012-2016)
EUROCOSMICS / B. van Eijk (chair) (2011-2016)
European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*) – Scientific Board / P. Mulders (2012-2015) (chair) (2016)
European Committee for Future Accelerators (ECFA) S. de Jong (2011) (2016), M. Merk, Th. Peitzmann (2011-2016), F. Linde (restricted ECFA) (2011-2014) (2016), S. Bentvelsen (2013-2014) (restricted ECFA) (2015-2016)
European Particle Physics Communication Network (EPPCN) / G. Bobbink, V. Mexner (2011-2016)
European Physical Journal – Scientific Advisory Committee / P. Mulders (past-chair) (2013-2015)
European Physical Society / E. de Wolf (2011-2016) (Executive Committee, Physics Education Board) / B. van Eijk (2011-2015), S. Bentvelsen (2016) (HEP Board)
European Physics Journal C / S. de Jong (associate editor) (2015-2016)
European Physics Journal – Scientific Advisory Committee / P. Mulders (chair) (2011-2012)
European Policy Management Authority for Grid Authentication in e-Science (EUGridPMA) / D. Groep (chair) (2011-2016)
European Research Council – Advanced Grants panel PE2 / S. de Jong(2011-2014)
European Review / A. Mischke (Guest editor) (2015-2016)
Excellentieprogramma Radboud Pre-University of Science / S. de Jong (projectleader) (2015-2016)

Excellent Science Days, Wroclaw, 2015 / A. Mischke (Member Scientific Advisory Committee) (2015)
FOM Adviescommissie FOm/v programma / E. de Wolf (2011-2012)
FOM Centrale Klachtadviescommissie (CKAC) / L. Wiggers (member) (2011-2016)
FOM network Theoretical High Energy Physics / E. Laenen (chair) (2011-2016), W. Beenakker, R. Kleiss (2011-2014)
FOM Raad van Bestuur / Th. Peitzmann (2011-2016), S. Bentvelsen (2011-2014)
FOM-Shell CSER (Computing Science Energy Research) / J. van den Brand (Board) (2015-2016)
Fonds Wetenschappelijk Onderzoek, Vlaanderen – Expertpanel Physics / E. de Wolf (2011—2016)
Fonds Wetenschappelijk Onderzoek, Vlaanderen – Expertpanel W&T2 / O. Igonkin (2015—2016)
FP7 Marie Curie Actions "Initial Training Networks" – Mathematics-Physics Panel, EU Research Executive Agency / A. Mischke (2012-2016)
Funding Agencies for Large Colliders / S. de Jong (member) (2016)
General Relativity and Gravitation (Springer) / R. Loll (associate editor) (2015-2016)
Genootschap ter bevordering van de Natuur-, Genees- en Heelkunde / E. Koffeman (board member) (2015-2016)
Gesellschaft für Schwerionenforschung, Darmstadt – Program Advisory Committee / Th. Peitzmann(2011-2012)
Gesellschaft für Schwerionenforschung, Darmstadt – Review Committee silicon tracking detector system for the Compressed Baryonic Matter experiment / G. Nooren (2012-2016)
GridKa Overview Board, Karlsruhe / K. Bos (2011)
Helmholtz Alliance for Astroparticle Physics, Germany (HAP) / E. de Wolf (Advisory Board) (2013-2016)
Helmholtz-Alliance for Physics at the Terascale – International Advisory Board / K. Bos (2011)
HiggsTools ITN network / E. Laenen (Supervisory Board) (2015-2016)
Instituto Nazionale di Fisica Nucleare (INFN) / F. Linde (member Technical Scientific Committee) (2012-2016)
Catholique de Louvain / E. Laenen (Scientific Advisory Committee) (2011- 2016)
Instituto Nazionale di Fisica Nucleare (INFN) / F. Linde (member Technical Scientific Committee) (2015-2016)
Interactions / V.Mexner (2011-2016)
International Conference on Acoustic and Radio EeV Neutrino Detection Activities (ARENA) / S. de Jong (programme committee) (2016)
International Conference on Computing in High Energy and Nuclear Physics (CHEP) / D. Groep (Int. Adv. Comm.) (2015-2016)
Int. Conf. on General Relativity and Gravitation (GR21) - Advisory Committee / R. Loll (2015)
International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions / M. van Leeuwen (International Advisory Committee) (2013-2015)
International Conference On Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter) / Th. Peitzmann (Int. Adv. Comm.) (2015-2016)
International Cosmic Ray Conference 2015 - local organising committee / S. de Jong, J. Hörandel (2015)
International Grid Trust Federation / D. Groep (chair) (2011-2014)
International Particle Physics Outreach Group (IPPOG) / V. Mexner (2011), S. Caron (2012 - 2015), C. Timmermans (2016)
International Society for General Relativity and Gravitation / J. Veitch(2013-2014)
International Symposium on Grids and Clouds / D. Groep (programme committee) (2015-2016)

International Union for Pure and Applied Physics - Commission on Astroparticle Physics / J. Hörandel(2013-2016)
International Union for Pure and Applied Physics (IUPAP) / P. Mulders (Liaison for the Netherlands) (2011-2012)
International Workshop on Heavy Quark Production in Heavy-Ion Collisions / P. Kuijer(2015-2016)
International Workshop on Radiation Imaging Detectors / J. Visschers (Scientific Advisory Committee) (2011-2012)
Interoperable Global Trust Federation (IGTF) / D. Groep (chair) (2015-2016)
Int. Workshop on Heavy Quark Production in Heavy-Ion Collisions / P. Kuijer, A. Mischke (co-chairs) (2012-2014)
Istituto Nazionale di Fisica Nucleare (INFN) / F. Linde (member Technical Scientific Committee) (2013-2014)
Kamioka Gravitational Wave Detector (KAGRA) / J. van den Brand (Program Advisory Board) (2015-2016)
Kernfysisch Versneller Instituut, Groningen – Scientific Advisory Committee (WAC) / P. Mulders(2011)
KNAW – Advisory Committee on Higher Education / B. de Wit(2012-2014)
KNAW – Commissie Evaluatie Wetenschappelijk Ruimteonderzoek in Nederland / S. de Jong (2011-2012)
Laboratori Nazionali di Frascati, Frascati – Scientific Committee / F. Linde(2011)
Laboratory Directors Group (LDG) / S. Bentvelsen(2016)
Landelijk coördinatorenoverleg HiSPARC / B. van Eijk (chair), J. van Holten(2011-2016)
LHCPhenoNet ITN network / E. Laenen (Supervisory Board) (2011-2014)
Living Reviews in Relativity - Editorial Board / R. Loll (member and subject editor for Quantum Gravity) (2015-2016)
Nationale Wetenschaps Agenda (NWA) / S. Bentvelsen (2016)
Natuur Leven Technologie – Regionaal Steunpunt Arnhem-Nijmegen / S. de Jong(2011-2014)
Nederlandse Natuurkundige Vereniging (NNV) – Advisory Board / M. Vreeswijk(2012-2016)
Nederlandse Natuurkundige Vereniging (NNV) / P. Mulders (secretary) (2011), S. de Jong (2011-2014), E. de Wolf (deputy chair) (2011-2016)
Nederlandse Natuurkundige Vereniging (NNV) – Sectie Onderwijs en Communicatie / S. de Jong (vice chair) (2011-2016)
Nederlandse Natuurkundige Vereniging (NNV) – Sectie Subatomaire Fysica / J. van Holten, I. van Vulpen (secretary), E. Koffeman (deputy chair) (2012-2014), F. Filthaut, A. Mischke, J. van Holten (board), I. van Vulpen (secretary), E. Koffeman (chair) (2015-2016)
Nederlands Tijdschrift voor Natuurkunde – Editorial Board / P. Decowski (2011-2014)
Netherlands eScience Center / J. Templon (eScience Integrator) (2012-2016)
Nijmegen Centre for Advanced Spectroscopy – Supervisory Board / F. Linde (chair) (2011-2016)
Nuclear Physics European Collaboration Committee (NuPECC) / Th. Peitzmann(2011), R. Snellings (2012-2016)
NWO - PC-GWI (permanente Commissie Grootschalige Wetenschappelijke Infrastructuur) / F. Linde (2016)
NWO - Vidi Committee / O. Igonkina (2016)
Open Grid Forum CA – OPS working group / D. Groep (co-chair) (2012-2016)
Open Grid Forum – Standards Function Security Area / D. Groep (director) (2011)
Particle Data Group / P. de Jong (2016)
Particle Physics Inside Products (P2IP BV) / F. Linde (2011), A. van Rijn (member of the board) (2011-2016)
PDF4LHC (Parton Density Functions for the LHC) workshop series – Organising committee / M. Botje(2011-2016)
Canada - Scientific Advisory Committee / R. Loll (chair) (2015-2016)
Permanente Commissie Grootschalige Wetenschappelijke Infrastructuur / F. Linde (2015-2016)
Platform Bèta Techniek – Ambassador / F. Linde, E. de Wolf (2011-2016)

Platform Universitaire Natuurkunde (PUN) / S. Bentvelsen (2013-2014), N. de Groot (2013-2016)
Precision theory for precision measurements in LHC and beyond, 2016, Quy-Nhon, Vietnam / P. Koppenburg (scientific advisory board) (2016)
Radboud University, Nijmegen - Committee Academic Integrity / R. Loll(2015-2016)
Radboud University, Nijmegen - Faculty Commission for Gender Equality / R. Loll (2015-2016)
Radboud University, Nijmegen - Opleidingscommissie natuur- en sterrenkunde / W. Beenakker (2015-2016)
Rencontres de Blois - Scientific Program Committee / D. Samtleben (2016)
Research Letters in Physics / A. Mischke (Member Editorial Board) (2015-2016)
Science Cafe Nijmegen / S. Caron (organizer) (2015-2016)
Scientific and Technical Advisory Committee European Gravitational Observatory / F. Linde (2015-2016)
Sectorplan committee for Physics and Chemistry (Commissie Breimer) / B. de Wit (2012-2016)
Steunpuntenraad / S. de Jong (chair) (2013-2014)
Stichting Conferenties en Zomerscholen over de Kernfysica (StCZK) / S. de Jong (secretary), P. Mulders (treasurer) (2011-2016)
Stichting Cosmic Sensation S. de Jong (chair, secretary and treasurer) (2011)
Stichting EGI.eu – Executive Board / A. van Rijn (vice chair) (2011-2014) (Dutch delegate in EGI Council) (2015-2016)
Stichting Hoge-Energie Fysica / J. van den Brand, R. Kleiss, , Th. Peitzmann, A. van Rijn (treasurer) (2011-2016), F. Linde (chair) (2011-2014), S. Bentvelsen (chair) (2015-2016)
Stichting Industriële Toepassing van Supergeleiding / B. van Eijk (2011-2016)
Stichting Natuurkunde.nl / F. Linde (chair), A. van Rijn (treasurer), M. Vreeswijk (editorial board) (2011-2016), S. de Jong (editorial board) (2013-2016)
Stichting Natuurkunde Olympiade Nederland / E. de Wolf (board member) (2013-2016)
Stichting Physica / P. Mulders (treasurer) (2013-2016), E. Koffeman (2015-2016)
Stichting Techniek Toernooi / E. de Wolf (chair) (2011)
Strangeness in Quark Matter conference, Berkeley, 2016 / A. Mischke (Member International Advisory Committee) (2015-2016)
TERENA Technical Committee (TTC) of the Geant Association / D. Groep (member) (2015-2016)
Thomas Jefferson National Accelerator Facility, Newport News – Program Advisory Committee / P. Mulders (2011)
Topsector High Tech Systems & Materials (HTSM) – Advanced Instrumentation / Precision Mechanics Board / J. van den Brand (2015-2016)
Topsector High Tech Systems & Materials (HTSM) – Scientific Committee and Roadmap Circuits & Components Committee / N. van Bakel(2012-2016)
University of Edinburgh – Higgs Centre / E. Laenen (associate member) (2012-2016)
Vereniging Gridforum Nederland / A. van Rijn (treasurer) (2011-2016)
Virgo STAC, Scientific & Technical Advisory Committee (EGO) / F. Linde (2016)
VUB Brussel / N. de Groot (Curriculum advisory board) (2015-2016)
Worldwide LHC Computing Grid / J. Templon (Management Board) (2011-2014) (Overview Board) (2015-2016)
Young Academy of Europe / A. Mischke (chair) (2012-2016)

WORKSHOPS/CONFERENCES ORGANISED BY NIKHEF

Name	year	place
APPS 2011, Amsterdam Particle Physics Symposium	2011	Amsterdam
BEAUTY 2011, 13th International Conference on B-Physics at Hadron Machines	2011	Amsterdam
Tini 80 Fest, 80th birthday Tini Veltman	2011	Amsterdam
APP15, Symposia on Astroparticle Physics in the Netherlands	2011	Leiden
APP14, Symposia on Astroparticle Physics in the Netherlands	2011	Groningen
ATLAS Flavour Tagging Workshop	2012	Nijmegen
Workshop on Heavy-flavour production in heavy ion collisions	2012	Utrecht
APP16, Symposia on Astroparticle Physics in the Netherlands	2012	Amsterdam
4th International Summer School on Astroparticle Physics	2012	Nijmegen
EGI Security Policy Workshop	2012	Amsterdam
CHEP 2013, 20th International Conference on Computing in High Energy and Nuclear Physics	2013	Amsterdam
The ATLAS Higgs to WW workshop	2013	Amsterdam
APP18, Symposia on Astroparticle Physics in the Netherlands	2013	Leiden
APP17, Symposia on Astroparticle Physics in the Netherlands	2013	Nijmegen
EGI CSIRT Security Incident Response workshop	2013	Amsterdam
TIPP'14, International Conference on Technology and Instrumentation in Particle Physics	2014	Amsterdam
Astroparticle Physics 2014	2014	Amsterdam
FELIX Development Kickoff Meeting	2014	Amsterdam
CERN school of physics 2014	2014	Garderen
FYSICA 2014	2014	Leiden
APP19 Symposia on Astroparticle Physics in the Netherlands	2014	Beekbergen
INFIERI mid-term review	2014	Amsterdam
JosFest [66th birthday of Jos Vermasen]	2015	Amsterdam
4th Dutch Grav. Wave meeting 2015	2015	Leiden
preREF 2015 meeting (preparatory meeting on Resummation, Evolution and Factorization	2015	Amsterdam

CONTINUE →

Name	year	place
APP20, Symposia on Astroparticle Physics in the Netherlands	2015	Berg en Dal
34th International Cosmic Ray Conference	2015	Den Haag
EUGridPMA 37th Plenary Meeting	2015	Amsterdam
WLCG Grid Deployment Board	2015	Amsterdam
EGI Security Policy and Vulnerability Analysis Workshop	2015	Amsterdam
3rd National eScience Symposium Accelerating Scientific Discovery	2015	Amsterdam
Medipix meeting	2015	Amsterdam
Dark Matter at the Large Hadron Collider 2016	2016	Amsterdam
FELIX Developers meeting	2016	Amsterdam
QCD evolution 2016 workshop	2016	Amsterdam
Lorentz Workshop Tomography of the quark-gluon plasma with heavy quarks	2016	Leiden
mPMT/NEUT workshop	2016	Amsterdam
APP21 Symposia on Astroparticle Physics in the Netherlands	2016	Woerden
7th International Conference on Acoustic and Radio EeV Neutrino Detection Activities 2016	2016	Groningen
EGI Security Policy workshop	2016	Amsterdam
1st AARC Project Conference	2016	Amsterdam
eIRG Open Workshop Amsterdam	2016	Amsterdam
ENLIGHT meeting	2016	Utrecht
White Rabbit workshop	2016	Amsterdam

GLOSSARY

AARC / (Authentication and Authorisation for Research and Collaboration)

Accelerator / A machine in which beams of charged particles are accelerated to high energies. Electric fields are used to accelerate the particles whilst magnets steer and focus them. A collider is a special type of accelerator where counter–rotating beams are accelerated and interact at designated collision points. A synchrotron is an accelerator in which the magnetic field bending the orbits of the particles increases with the energy of the particles. This keeps the particles moving in a closed orbit.

ALICE / (A Large Ion Collider Experiment) One of the four major experiments that uses the LHC.

AMS / The Alpha Magnetic Spectrometer, also designated AMS-02, is a particle physics experiment module, mounted on the International Space Station (ISS) in 2011. It is designed to measure antimatter in cosmic rays and search for evidence of dark matter. The CO_2 cooling system for the silicon trackers of this experiment was developed by the R&D group of Nikhef.

AMS–IX / (Amsterdam Internet Exchange) The main place in the Netherlands for Internet Service Providers to interconnect and exchange IP traffic with each other at a national or international level.

Annihilation / A process in which a particle meets its corresponding antiparticle and both disappear. The resulting energy appears in some other form: as a different particle and its antiparticle (and their energy), as many mesons, or as a single neutral boson such as a Z-boson. The produced particles may be any combination allowed by conservation of energy and momentum.

ANTARES / (Astronomy with a Neutrino Telescope and Abyss Environmental Research) Large area water Cherenkov detector in the deep Mediterranean Sea near Toulon, optimised for the detection of muons resulting from interactions of high–energy cosmic neutrinos.

Antimatter / Every kind of matter particle has a corresponding antiparticle. Charged antiparticles have the opposite electric charge as their matter counterparts. Although antiparticles are extremely rare in the universe today, matter and antimatter are believed to have been created in equal amounts in the Big Bang.

Antiproton / The antiparticle of the proton.

APP / (AstroParticle Physics) APPEC (Astroparticle Physics European Coordination) The assembly of 17 funding agencies, governmental institutions and institutes from 14 European countries for coordinating efforts in astroparticle physics, created in 2012.

ARCA / (Astroparticle Research with Cosmics in the Abyss) The ARCA neutrino telescope of KM3NeT is dedicated to the search for very high-energy cosmic neutrinos.

ASIC / (Application-Specific Integrated Circuit) A custom or semicustom integrated circuit, such as a cell or gate array, created for a specific application.

ASPERA / Sixth Framework Programme for coordination across European funding agencies for financing astroparticle physics. The seventh Framework Programme started in 2009 and is called ASPERA-2.

ATLAS / (A Toroidal LHC ApparatuS) One of the four major experiments that uses the LHC.

BaBar / Detector at SLAC's B Factory. Named for the elephant in Laurent DeBrunhoff's children's books. Operation stopped in 2008.

Baryon / See Particles.

Beam / The particles in an accelerator are grouped together in a beam. Beams can contain billions of particles and are divided into discrete portions called bunches. Each bunch is typically several centimeters long and can be just a few μm in diameter.

BIC / Business Incubation Centres (BICs) of CERN technologies in nine European countries assist entrepreneurs and small high-tech businesses in taking innovative technologies from technical concept to market reality using CERN technologies or expertise.

Big Bang / The name given to the explosive origin of the universe.

Boson / The general name for any particle with a spin of an integer number (0, 1 or 2...) of quantum units of angular momentum (named for Indian physicist S.N. Bose). The carrier particles of all interactions are bosons. Mesons are also bosons.

Calorimeter / An instrument for measuring the amount of energy carried by a particle.

Cherenkov radiation / Light emitted by fast–moving charged particles traversing a dense transparent medium faster than the speed of light in that medium.

CKM matrix / The weak force is responsible for the decay of matter: unstable particles made of heavy quarks and antiquarks decay into particles made of their lighter cousins. The rates of these decay processes are related to a set of numbers called the Cabibbo-Kobayashi-Maskawa (CKM) matrix, named for the three physicists who introduced it. The numbers are often shown in a graphical form called the unitarity triangle. The area of the triangle is a measure of the amount of CP violation caused by the weak force. This CP violation partly explains why we live in a matter-dominated universe rather than one full of antimatter or radiation.

CLIC / (Compact Linear Collider) A feasibility study aiming at the development of a realistic technology at an affordable cost for an electron–positron linear collider for physics at multi–TeV energies.

CNC / (Computer Numeric Control)

Collider / See Accelerator.

Cosmic ray / A high–energy particle that strikes the Earth's atmosphere from space, producing many secondary particles, also called cosmic rays.

CP violation / The CP operation is a combination of charge conjugation (C) and parity (P). In most interactions, CP is conserved, which means that the interaction proceeds exactly the same way if the CP operation is performed on the interacting particles. If CP is conserved, particles with opposite charge and parity will interact in the same way as the original particles. CP violation occurs when an interaction proceeds differently when the CP operation is performed - particles with opposite charge and parity interact differently than the original particles. CP violation was first observed in neutral kaon systems. This subtle effect betrays nature's preference for matter over antimatter.

Dark Matter and Dark Energy / Only 4% of the matter in the universe is visible. The rest is known as Dark Matter and Dark Energy. Finding out what it consists of is a major question for modern science.

dCache / A data file caching system that acts as an intelligent manager between the user and the data storage facilities, optimizing the location of staged copies according to an access profile

Detector / A device used to measure properties of particles. Some detectors measure the tracks left behind by particles, others measure energy. The term 'detector' is also used to describe the huge composite devices made up of many smaller detector elements. Examples are the ATLAS, the ALICE and the LHCb detectors.

eEDM / Electron's electric dipole moment experiment at the Van Swinderen institute of the University of Groningen.

EoI / (Expression of Interest)

ET (Einstein Telescope) / Design project for a third generation gravitational wave observatory consisting of three –underground and typically 10 km long– cryogenic xylophone interferometers in a triangular shape.

eV (Electronvolt) / A unit of energy or mass used in particle physics. One eV is extremely small, and units of million electronvolts, MeV, thousand MeV = 1 GeV, or million MeV = 1 TeV, are more common in particle physics. The latest generation of particle accelerators reaches up to several TeV. One TeV is about the kinetic energy of a flying mosquito.

Fermion / General name for a particle that is a matter constituent, characterised by spin in odd half integer quantum units. Named for Italian physicist Enrico Fermi. Quarks, leptons and baryons are all fermions.

Forces / There are four fundamental forces in nature. Gravity is the most familiar to us, but it is the weakest. Electromagnetism is the force responsible for thunderstorms and carrying electricity into our homes. The two other forces, weak and strong, are connected to the atomic nucleus.
The strong force binds the nucleus together, whereas the weak force causes some nuclei to break up. The weak force is important in the energy–generating processes of stars, including the Sun. Physicists would like to find a theory that can explain all these forces in one common ↗ framework. A big step forward was made in the late 1970s when the electroweak theory uniting the electromagnetic and weak forces was proposed. This was later confirmed in a Nobel Prize–winning experiment at CERN.

FORM / FORM is a symbolic manipulation system. It reads text files containing definitions of mathematical expressions as well as statements that tell it how to manipulate these expressions.

FPGA (Field Programmable Gate Array) / A general-purpose logic device that can be configured by the end user to perform many, different, complex logic functions; often used for prototyping logic hardware.

Fte (Full Time Equivalent) / Unit of manpower.

Gluon / See Particles.

GlusterFS / A scale-out network-attached storage file system.

Gravitational wave / The gravitational analogue of an electromagnetic wave whereby gravitational radiation is emitted at the speed of light from any mass that undergoes rapid acceleration.

Grid / A service for sharing computer power and data storage capacity over the Internet.

Hadron / A subatomic particle that contains quarks, antiquarks, and gluons, and so experiences the strong force (see also Particles).

High–Energy Physics / A branch of science studying the interactions of fundamental particles; called 'high–energy' because very powerful accelerators produce very fast, energetic particles probing deeply into other particles.

Higgs boson / A particle predicted in 1964 independently by theoreticians Brout, Englert and Higgs in order to explain the mechanism by which particles acquire mass. In 2012 the ATLAS and CMS experiments at the LHC announced the discovery of a particle with mass 125 GeV that fits the properties of this Higgs boson. The particle plays a central role in the Standard Model of elementary particle physics. In 2013 Englert and Higgs received the Nobel Prize "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted ↗ fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

HiSPARC (High School Project on Astrophysics Research with Cosmics) / Cosmic–ray experiment with schools in the Netherlands, Denmark and UK.

HL-LHC (High-Luminosity LHC) / A major upgrade of the LHC to increase its luminosity (rate of collisions) by a factor of 10 beyond the original design value.

IceCube / The IceCube Neutrino Observatory is constructed at the South-Pole station in Antarctica. Its thousands of photomultiplier sensors are distributed over a cubic kilometre of volume under the Antarctic ice.

ILC / International Linear Collider, now under study. A possible future electron–positron accelerator, proposed to be built as an international project.

Kaon / A meson containing a strange quark (or antiquark). Neutral kaons come in two kinds, long–lived and short–lived. The long–lived ones occasionally decay into two pions, a CP–violating process (see also Particles).

KM3NeT (Cubic Kilometre Neutrino Telescope) / Planned European deep–sea neutrino telescope with a volume of several cubic kilometres at the bottom of the Mediterranean Sea, distributed over three locations offshore the coasts of France, Italy and Greece,

LEP (Large Electron–Positron) / An electron-positron collider, which ran at CERN until 2000. Its tunnel has been reused for the LHC.

Lepton / A class of elementary particles that includes the electron. Leptons are particles of matter that do not feel the strong force (see also Particles).

LHC (Large Hadron Collider) / CERN's biggest accelerator, started in 2008.

LHCb (Large Hadron Collider beauty) / One of the four major experiments that uses the LHC.

LIGO (Laser Interferometer Gravitational-Wave Observatory) / The observatory consists of two LIGO detectors: ↗ Michelson-type interferometers with arms 4 km long, at Hanford, Washington, and Livingston, Louisiana.

LISA (Laser Interferometer Space Antenna) / ESA-only gravitational wave space mission, orbiting around the Sun as a giant equilateral triangle 1 million km on a side. Candidate for launch in 2028.

M&O / Maintenance and Operations: a term used in large scientific collaborations to denote the cost to maintain and operate ('run') a detector or telescope.

Majorana particle / A fermion that is its own antiparticle, predicted by Majorana in 1937.

Medipix / A family of photon counting pixel detectors based on the Medipix CMOS read-out chips that can be provided with a signal from either a semi-conductor sensor or ionisation products in a gas volume. The detectors are developed by an international collaboration, hosted by CERN, and including Nikhef. Medipix-3 is the latest version.

MEMS (MicroElectroMechanical System) / The technology of microscopic devices, today almost any miniaturized device (based on Si technology or traditional precision engineering, chemical or mechanical) is referred to as a MEMS device.

Meson / See Particles.

microHV / Miniature High-Voltage power supply

MultiSAS (Multi-stage Seismic Attenuation System)

Muon / A particle similar to the electron, but some 200 times more massive (see also Particles).

Muon chamber / A device that identifies muons, and together with a magnetic system creates a muon spectrometer to measure momenta.

Neutrino / Uncharged, weakly interacting lepton, most commonly produced in nuclear reactions such as those in the Sun. There are three known flavours of neutrino, corresponding to the three flavours of leptons. Recent experimental results indicate that all neutrinos have tiny masses (see also Particles).

NNLO (Next–to–Next-to-Leading Order) / Third-order calculations in perturbative QED and QCD.

NWO / The Netherlands Organisation for Scientific Research funds thousands of top researchers at universities and institutes and steers the course of Dutch science by means of subsidies and research programmes.

NWO-I / Institute organisation of NWO; formerly FOM

Nucleon / The collective name for protons and neutrons.

ORCA (Oscillation Research with Cosmics in the Abyss) / The ORCA telescope of KM3NeT is dedicated to the study of neutrino properties exploiting neutrinos generated in the Earth's atmosphere using optimized KM3NeT sensor strings

Particles / There are two groups of elementary particles, quarks and leptons, with three families each. The quarks are named up and down, charm and strange, top and bottom (or beauty). The leptons are electron and electron neutrino, muon and muon neutrino, tau and tau neutrino. There are four fundamental forces, or interactions, between particles, which are carried by special particles called bosons. Electromagnetism is carried by the photon, the weak force by the charged W and neutral Z bosons, the strong force by the gluons and gravity is probably carried by the graviton, which has not yet been discovered. Hadrons are particles that feel the strong force. They include mesons, which are composite particles made up of a quark–antiquark pair, and baryons, which are ↗

particles containing three quarks. Pions and kaons are types of meson. Neutrons and protons (the constituents of ordinary matter) are baryons; neutrons contain one up and two down quarks; protons two up and one down quark.

Photon / See Particles.

Pierre Auger Observatory / International experiment in Argentina to track down the origin of ultra–high–energy cosmic rays.

Pion / See Particles.

Positron / The antiparticle of the electron.

Quantum electrodynamics (QED) / The theory of the electromagnetic interaction.

Quantum chromodynamics (QCD) / The theory for the strong interaction analogous to QED.

Quark / The basic building block of matter (see also Particles).

Quark–gluon plasma (QGP) / A new kind of plasma, in which protons and neutrons are believed to break up into their constituent parts. QGP is believed to have existed just after the Big Bang.

Rasnik (Red Alignment System Nikhef) / Optical alignment system where a pattern is projected by a lens on a CCD and deviations measured.

RHIC / Brookhaven's Relativistic Heavy Ion Collider; began operation in 2000. RHIC collides beams of heavy ions (Al, Cu, Au and U ions) to study what the universe looked like in the first few moments after the Big Bang.

Sigma (σ) / In statistics, a measure of the dispersion or variation in a distribution.

SLAC / The Stanford Linear Accelerator Center in Stanford, California.

SLD (SLAC Large Detector) / A particle physics detector at the interaction point of the Stanford Linear Collider (SLC), where electrons and positrons collided. The SLC closed down in the late 1990's.

SME / Small and Medium-sized enterprises.

Spectrometer / In particle physics, a detector system containing a magnetic field to measure momenta of particles.

Spin / Intrinsic angular momentum of a particle.

SPIRES / Database of particle physics publications since the late 1960's; now INSPIRE.

Standard Model / A collection of theories that embodies all of our current understanding about the behaviour of fundamental particles.

Stoomboot / Local Tier-3 analysis cluster

String Theory / A theory of elementary particles incorporating relativity and quantum mechanics in which the particles are viewed not as points but as extended objects. String theory is a possible framework for constructing unified theories that include both the microscopic forces and gravity (see also Forces).

Supersymmetry
Supersymmetry (often abbreviated SUSY) / is a symmetry that relates elementary particles of one spin to other particles that differ by half a unit of spin and are known as superpartners (e.g. squarks).

SURF / The organization in the Netherlands responsible for the national e-infrastructure: computing, data and networking services for research and (higher) education.

SURFnet / The Dutch National Research and Education Network organization, a subsidiary of SURF.

SURFsara / Organization providing computing and data services to Dutch academic institutions, a subsidiary of SURF.

Tevatron / Fermilab's 2-TeV proton-antiproton accelerator near Chicago, closed in 2011.

Tier–1 / First tier (category) in the LHC regional computing centers. Tier–0 is the facility at CERN collecting, reconstructing and storing the data.

Topsector / The Topsector policy of the Dutch government aims to strengthen collaboration between companies, researchers and the government in nine innovative sectors.

Trigger / An electronic system for spotting potentially interesting collisions in a particle detector and triggering the detector's read–out system.

UHECR (Ultra-High-Energy Cosmic Ray)

Vertex detector / A detector placed close to the collision point in a colliding beam experiment so that tracks coming from the decay of a short–lived particle produced in the collision can be accurately reconstructed and seen to emerge from a 'vertex' point that is different from the collision point.

Vernieuwingsimpuls / Personal grant scheme of NWO: VENI (recently obtained PhD), VIDI (several years of experience) and VICI (able to develop own line of research).

Virgo / Detector near Pisa for gravitational waves: a Michelson laser interferometer made of two orthogonal arms, each 3 km long.

W boson / A carrier particle of weak interactions; involved in all electric–charge–changing weak processes.

White Rabbit / White Rabbit is a fully deterministic Ethernet-based network for general purpose data transfer and synchronization. It can synchronize over 1000 nodes with sub-ns accuracy over fiber lengths of up to 10 km. Named after the time-obsessed character in Alice in Wonderland.

WIMP / Weakly Interacting Massive Particles are the most compelling candidates for Dark Matter particles. They can interact with normal matter through the weak nuclear force and through gravity and are often inherent to models extending the Standard Model.

WISE (Women In Science Excel) / Tenure track programme of NWO for female scientists.

WLCG (Worldwide LHC Computing Grid) / The mission of the WLCG is to provide data-storage and analysis infrastructure for the entire high-energy physics community using the LHC.

XENON / A series of experiments aiming at direct detection of Weakly Interacting Massive Particles (WIMPs). The detectors are located in the Gran Sasso laboratory in Italy and use xenon as the target material.

Z boson
A carrier particle of weak interactions; involved in all weak processes that do not change flavour and charge.

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Nikhef
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This document is created for the self-evaluation of Nikhef. The National Institute for Subatomic Physics Nikhef is a partnership between the Foundation for Fundamental Research on Matter (FOM), now the Institutes Organisation of NWO (NWO-I), and five universities: the Radboud University (RU), University of Amsterdam (UvA), Utrecht University (UU), VU University Amsterdam (VU) and University of Groningen (RUG) (since February 2016). Nikhef is based at Amsterdam Science Park.

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

Partners:


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