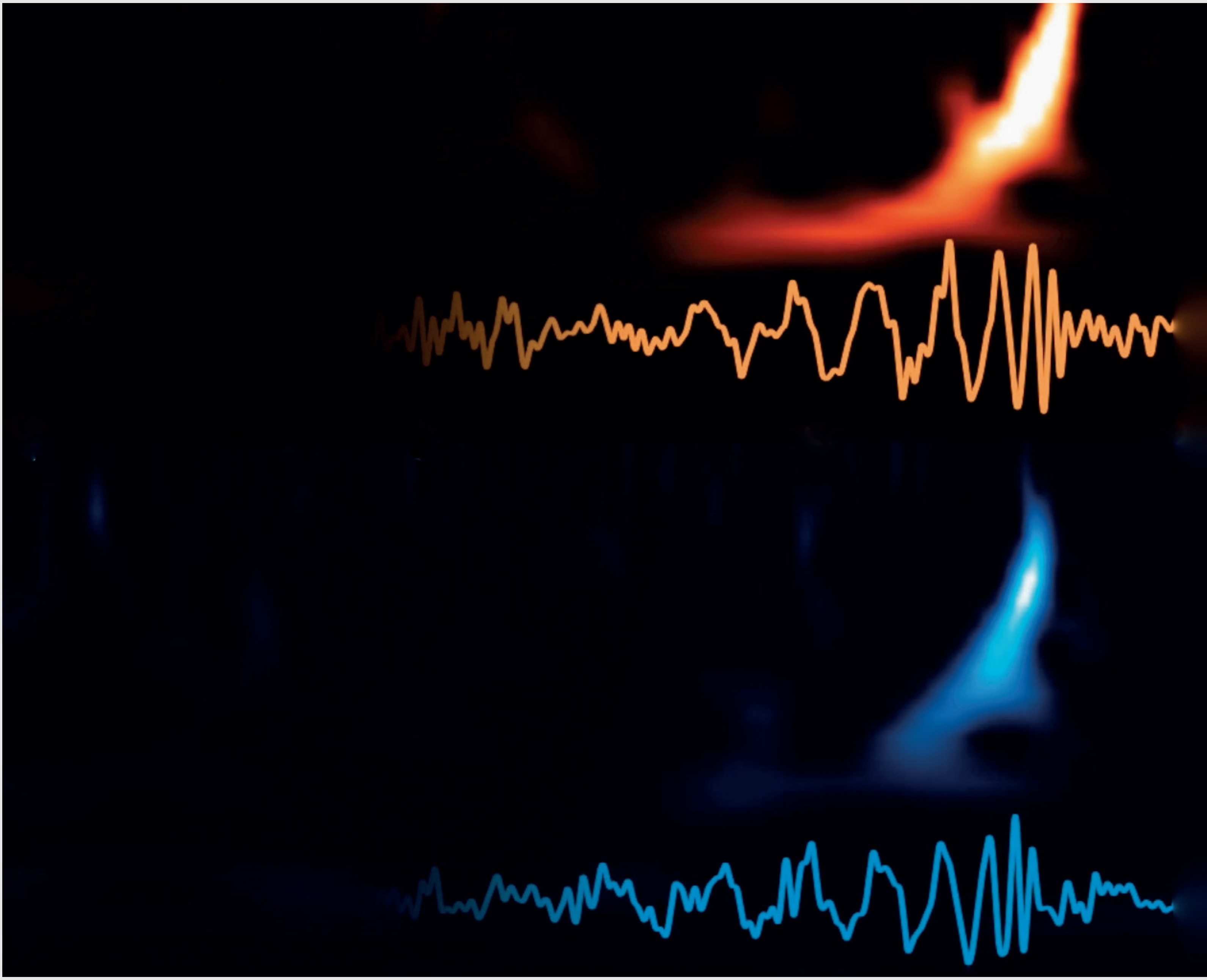
ANNUAL REPORT
2016



Nikhef

National Institute for Subatomic Physics

Annual Report
2016

National Institute
for Subatomic Physics
Nikhef

Colophon

Nikhef
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National Institute for Subatomic Physics

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Cover: First observation of gravitational waves by the LIGO-Virgo collaboration.

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.

Contents

Introduction

The discovery of the gravitational waves was the top major scientific breakthrough of 2016. On 11 February, all newspapers reported on the observation of the astonishing merger of two heavy black holes, as detected and analysed by the LIGO-Virgo consortium. Front-page articles, the daily show DWDD, background information, I believe almost all people in the Netherlands have seen the announcement of this discovery. Nikhef played a major role in this discovery by producing the first test of General Relativity of Einstein under these extreme conditions as well as by assessing the consequences in astroparticle physics.

As a matter of fact, I remember six months before, September 2015, when Jo van den Brand came to my office with a mix of enthusiasm and unbelief. He showed me the loud chirp of the very first gravitational wave signals detected a few days before on 14 September. It took the consortium some time to check and analyse the signal before releasing the discovery; but then a new and very exciting era in astroparticle physics had begun. It is clear that the advanced Virgo detector has a bright future as it will bring major improvements in future detections of gravitational waves. This annual report contains the status of Virgo and details of the discovery of gravitational waves with an interview of Nikhef scientists.

And that is not the only highlight of this year. The LHC machine performed extremely well where the number of collisions between the protons exceeded expectations. The challenge of the Nikhef teams of ATLAS, LHCb and ALICE has become twofold; to continue to play a central role in the data analysis as well as to design and construct the hardware parts that will be installed during the Long Shutdown periods of LHC (2018–2020 and 2024–2026). The data taken so far at the experiments contains a huge amount of information; the precision on measurements of the Higgs particle is increasing rapidly, new results on differences between matter and anti-matter are produced, the quark-gluon plasma is better described as a liquid, etc. Details of these advancements can be found in this report as well.

Further, on astroparticle experiments, towards the end of the year the preparations of the XENON1T Dark Matter experiment in Gran Sasso were concluded and the science run could be started. So hence, if it exists, Dark Matter may actually be found very soon. The Auger cosmic ray experiment in Argentina continues to collect data of ultra-high energetic cosmic rays, with an increased understanding of radio signals. The neutrino telescope KM3NeT advanced impressively as it has deployed new strings with Digital Optical Modules near Malta. The technical workshops at Nikhef took a large responsibility in this experiment. In addition, KM3NeT went through an important administrative hurdle as it was recognised as a major European Research Infrastructure and obtained the corresponding ESFRI status.

As a matter of fact, for the longer term future Nikhef has positioned three large infrastructures on the NWO National Roadmap, that was released in December of this year. Not only KM3NeT and the upgrades of the LHC experiments are on this roadmap, but also the Einstein Telescope entered the list, the third generation ground-based interferometer to observe gravitational waves with a much higher precision.

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:

- **Accelerator-based particle physics - Studying interactions in particle collision processes at particle accelerators, in particular at CERN;**
- **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, civil society and general public, is an integral part of Nikhef's mission.

This all means that Nikhef is in good shape. With the strong theory phenomenology department, the physics data-processing group with the Tier1 and the detector R&D department with a number of valorisation projects, the institute contains a beautiful portfolio to fulfil its mission. Towards the end of the year the number of programmes was further extended by the electron Electric Dipole Moment programme. The measurement of this quantity is being prepared for in Groningen at the Van Swinderen Institute, as you will also find in this report.

Actually, the new partnership with the Van Swinderen Institute of the University of Groningen is another highlight of this year. The Nikhef partnership with now five universities has therefore been renewed and signed by those universities earlier in 2016. The Van Swinderen Institute joined FOM, the University of Amsterdam, the VU University Amsterdam, the Radboud University and the University Utrecht. Our Nikhef annual meeting was held in Groningen this year, organised by our new colleagues. It was an excellent opportunity to get to know each other a bit better.

During the year also the preparations for a new NWO organisation took place, including the transition of FOM to NWO-I, the institute organisation. In the new organization, Nikhef will be part of NWO-I as one of the nine institutes, accountable directly to the board of NWO. Details of this migration have been worked out over the year, that will take effect early 2017.

The *"Nationale Wetenschaps Agenda"* NWA is getting more attention over the last year, as it has the ambition to seriously increase the funding in research and innovation in the Netherlands. As you can also read in this annual report, the NWA route *"Building Blocks of Matter and Fundamentals of Space and Time"*, with a lot of Nikhef activities, is getting important in this discussion.

Lastly a few more personal remarks. I am very pleased that this annual report also contains the activities of the Technical Groups at Nikhef, as the Computer , Electronics and Mechanical Technology departments form the backbone of our institute. Further I enjoy my *'spiegelmoment'*, a regular short presentation in Dutch where I can share latest news, welcome new colleagues and talk about developments at Nikhef. The new Nikhef website, that gives our institute a modern look and feel from the outside, is launched and it is good to see that our refurbished Spectrum with coffee machine is used extensively.

Thanks to everybody for all contributions to Nikhef over the year!

Stan Bentvelsen

Opening up a new window on the

Now that their 2016 detection has given us a solid proof of concept, gravitational waves are opening up a new window on the cosmos.

By George van Hal

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. And yet, physicists working on LIGO, Virgo and potential follow-up detectors like Einstein Telescope are only just getting started. The next few years might hold even greater scientific rewards, as the existing gravitational wave detectors gradually improve their sensitivities, and new detectors join the worldwide network. As a new window on our skies opens up, these detectors are set to give us everything from clear insights into the internal structure of neutron stars and the validity of Einstein's theory of general relativity, to further breakthrough discoveries about the primordial mechanics of the very early universe.

A world first

"Announcing that we had directly detected gravitational waves for the first time, was a truly great moment", says Nikhef physicist Chris Van Den

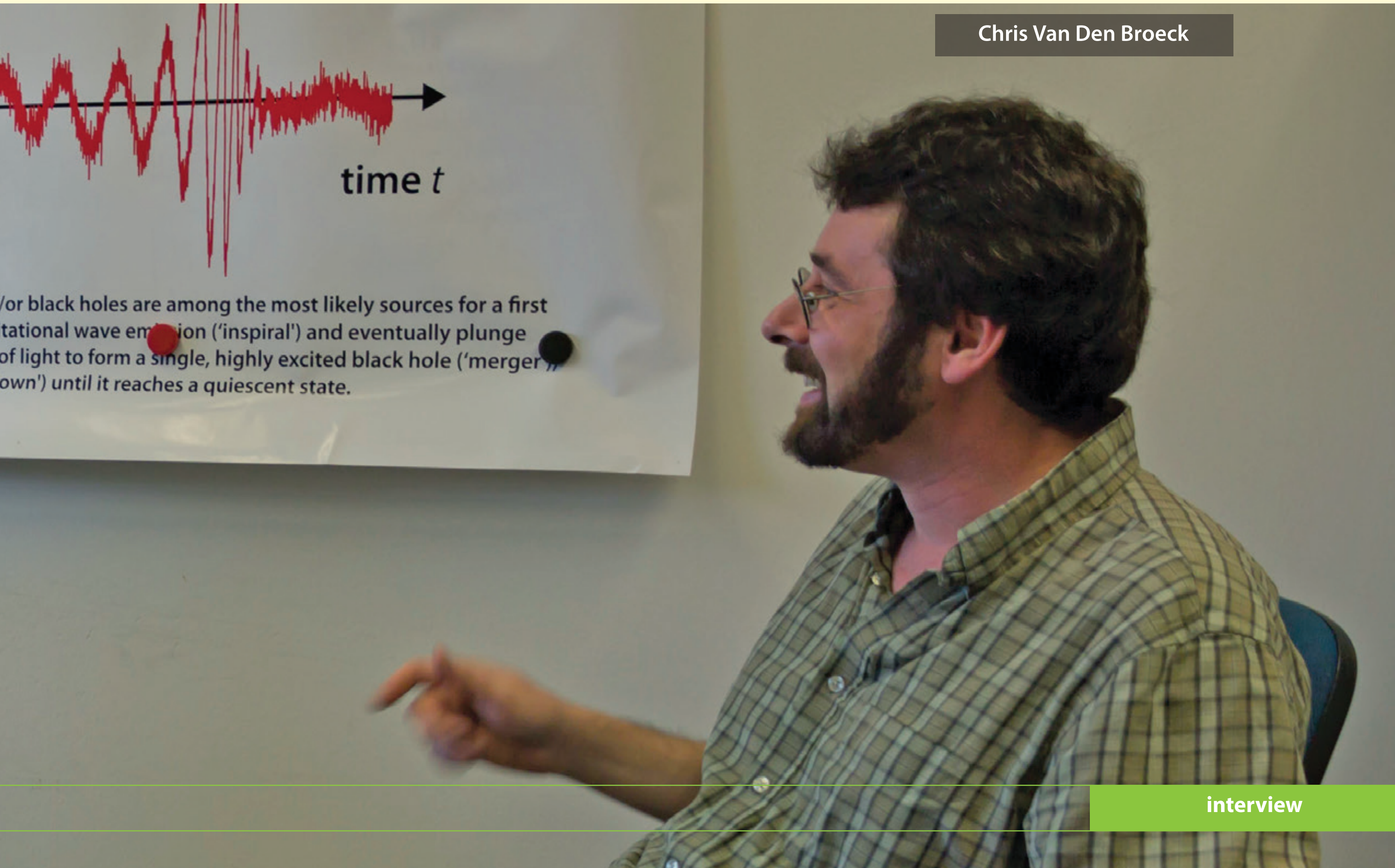
Jo van den Brand

cosmos

Broeck, who spearheaded scientific analyses of the measurements. "We were finally allowed to talk about it in public. And of course, everyone was interested in seeing our results."

While the wave itself hit the North-American based LIGO detectors in September 2015, scientists involved in the LIGO and Virgo collaborations had to sit and wait until February 2016 when they had finished their painstaking scientific analyses and were allowed to share their findings with the world. "We knew on the first day that what we had was real", says detection committee member and Nikhef programme leader for Gravitational Waves Jo van den Brand, who oversaw all the scientific analyses. "And we knew it was from a source we never would have expected; not a collision of neutron stars, but a collision of black holes."

"That first week was pure euphoria", says Van Den Broeck. "But after that, the real work started." The first order of business was to hit that time-honoured physics benchmark of statistical measurement reliability: a 5 sigma result. "Reaching that bar required some work", Van Den Broeck remembers.



Chris Van Den Broeck

Still, making sure they had their measurement in statistical order wasn't the only thing that needed to be done. "The day after we published our results, we published 12 companion papers", says Van Den Broeck. Those papers covered everything from the astrophysical implications of the measurement to a world-first analysis run by Van Den Broeck and colleagues; a rigorous test of Einstein's theory of general relativity, which probed the genuinely strong-field dynamics of space-time for the first time.

"We knew we could test the theory in ways that had never been done before", says Van Den Broeck. Earlier tests of the effects predicted by general relativity were all done in weak field regimes. Physicists were looking at things like the twisting of light paths due to the gravity of stars, or the movement of planets: low mass, low energy situations where objects were moving relatively slowly when compared to the speed of light. "With this result we were observing the strongest possible curvature of space-time in a physical system. We were watching giant masses move at half-light speed. It was a unique opportunity."

The new analyses by Van Den Broeck and colleagues turned out to be the most popular – in citations – of the 12 companion papers. Not surprising, when considering their world record result. "We now know that also in the strong-field regime, Einstein's theory of general relativity cannot be off by more than 10 percent", says Van Den Broeck. "Anything larger we would have seen."

And the scientists had another surprise in store. As media all over the world were scrambling to report on their February results, they knew of a second detection. "But we could not yet discuss it", says Van Den Broeck. That second signal was also detected in 2015, on 26 December to be precise. "A beautiful Christmas present", according to Van den Brand.

And because the masses of the black holes involved were much smaller, the wave they measured was much longer, giving Van Den Broeck the opportunity to test some other general relativity predictions about the way the inspiral of black holes happens before a collision. So far, Einstein's predictions are holding up.

New results

These detections, while massively interesting in and of themselves, also prove that the current generation of gravitational wave detectors is up to the task of measuring those tiny ripples in space-time. Because of that, a new window is opening up on the cosmos, one beyond the confines of the electromagnetic band that scientists have been using for years – and physicists and astronomers alike are hoping for unexpected results.

"I'd be surprised if there weren't any surprises", Van den Brand says. Because of that, physicists are keeping an open mind while looking for new signals, so as not to miss any waves with unexpected shapes. "Every time the old electromagnetic telescopes opened up a new wavelength range, they found a new kind of object", Van Den Broeck says. "And what we're doing here isn't just a broadening of the spectrum, it's utilizing an entirely new messenger, the gravitational field."

In the short term, however, Van den Brand and Van Den Broeck are expecting spectacular new insights about the objects they already know of. "We want to

December 2016 issue of Science Magazine: the discovery of gravitational waves as the breakthrough of the year.

see more black hole mergers", says Van den Brand. And if the two signals from 2015 are any indication, new observations from a measurement run that started at the end of 2016, are set to bring around several new signals by the summer of 2017.

"Those might give us a clue where these black holes are from and how they're formed", says Van den Brand. That's a relevant question, given the fact that scientists were not expecting to see such massive black holes merging. "The first one especially, with its 65 solar masses in total, was a big surprise", says Van Den Broeck.

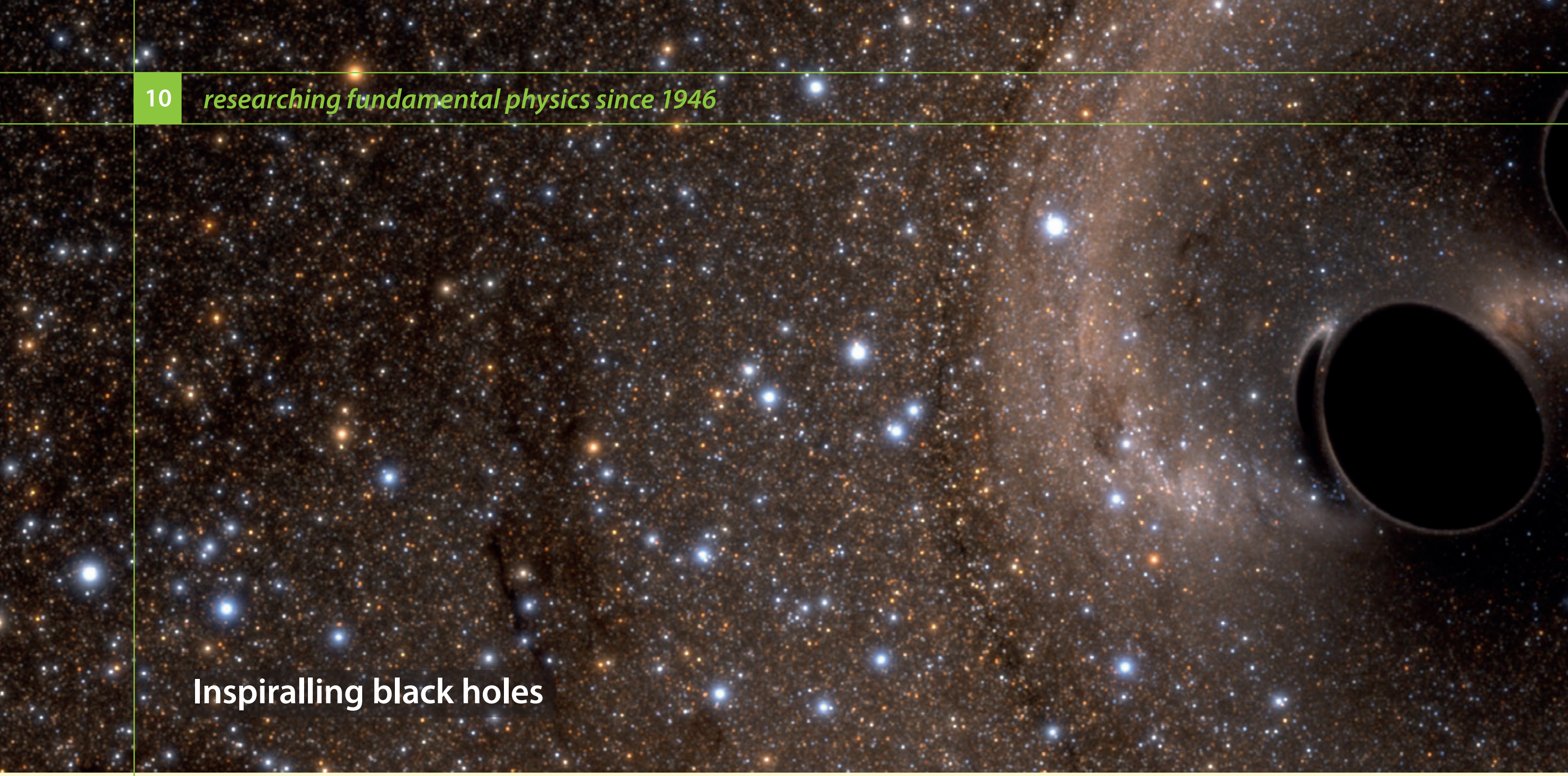
Currently there are some theories as to how these black holes may form, but no definite results. One theory states that they may form from two heavy stars in a binary system, while others think they might form in star clusters, where they eventually run into each other. By looking at the spins of both black holes – and if they're aligned or misaligned – researchers might finally learn which of these two scenarios fits the facts. The physicists are also hoping to catch a few colliding neutron stars. "At this moment, we know very little about their internal structure", says Van Den Broeck. "There's all kinds of theoretical models for their equations of state, and with current measuring techniques there's little opportunity to distinguish between them."

Gravitational waves will allow physicist to peer much deeper into these mysterious objects. "When these stars move very close to each other, they pull on each other and start to deform", explains Van Den Broeck. "How strongly they deform is determined by their equation of state". This deformation in turn impacts the trajectory of these neutron stars and the shape of the gravitational waves they send out. "Gravitational waves give us a way to understand which of our theoretical models are real", says Van Den Broeck.

Virgo update

Next year the third gravitational wave detector will go online, the Advanced Virgo at Cascina near Pisa. This will give physicists the opportunity to accurately triangulate the location of a detected signal. They will be able to ask astronomers to independently observe the same area in the sky with other instruments.

"The astronomical community is showing a lot of interest in what our instruments can do", says Van Den Broeck. More than 80 astronomy collaborations, including big ones like Swift, Fermi and LOFAR, have agreed to look at the approximate location of the source indicated by the LIGO-Virgo network.
"In our group, we're working with astronomers and astrophysicists from Nijmegen, like Paul Groot and Gijs Nelemans", adds Van den Brand. "Our collaboration with these communities is one of the great things about this project."



Inspiralling black holes

Before astronomers can start their more precise searches, Advanced Virgo needs to come online. In the original planning, it should have been up and running already, but the team experienced a major setback in 2016. “The quartz wires we were using to suspend the mirrors in the detector, were breaking after a week or two inside the vacuum”, says Van den Brand. After a long analysis, the physicists discovered the problem: the vacuum pumps they were using gave off minute dust particles, which were hitting the wires. “We now need to encase, or replace, the vacuum pumps”, says Van den Brand. “But at least we finally have a solution.”

As things look now, Advanced Virgo will begin measuring in March. Perhaps at a slightly lower sensitivity than planned, but enough to triangulate a signal. And if it proves to work as promised, the physicists will slowly increase the sensitivity – an important step, because more sensitive detectors can look for signals in a larger volume of space.

The current instruments, Advanced LIGO and Advanced Virgo, are set to continue running until at least 2022. “We’ll be at our highest sensitivity then”, says Van Den Broeck, but plans are already underway for a second life after that time. “We can inject squeezed light, change the mirrors, change the lasers – there’s all kinds of options to improve these detectors when the time comes”, says Van den Brand. In the meantime, physicists are setting their sights on the next generation of gravitational wave detectors, including the space-based telescope LISA, which, according to Van den Brand, has ‘fantastic prospects’ and is garnering a lot of enthusiasm. The most promising new detector is Einstein Telescope, which – like the Cosmic Explorer in the US – 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.”

The dark ages of the Universe and beyond

Detectors like Einstein Telescope will allow physicists to look at a time in the history of our Universe just after the Big Bang, but before the first stars were born. Those early times, which astronomers call the dark ages, are

still mostly a mystery. At that time the Universe was very dense, and gravity was the main driver of structure formation. As of yet, no one knows what might be glimpsed from looking at this strange period.

"I'm hoping to see primordial black holes", says Van den Brand. These early black holes might prove to be the seeds for the supermassive black holes in the centres of galaxies that we know are there today. If primordial black holes existed, they could have grown throughout the 15 billion year history of the Universe, into the huge 'monsters' we see today.

"Einstein Telescope will give us the opportunity to discover completely new physics", says Van den Brand. He believes the new instrument may also provide an opportunity to observe primordial gravitational waves, which – if they exist – will have originated a split-second after the Big Bang. It is generally assumed that, in that same timeframe, the Universe underwent a period of inflation, during which space-time grew exponentially. "Inflation was driven by the inflaton field, which has a corresponding particle, the inflaton", says Van Den Broeck. "When this inflaton decays into other particles, gravitational waves should be created, which could still be measurable today." Measuring those kinds of primordial gravitational waves may be the only way to prove this popular idea of cosmic inflation.

Such a discovery is certainly possible, given the fact that the energy scales Einstein Telescope will uncover are unlike anything mankind has looked at before. "It's twelve orders of magnitude higher than what they"re currently observing at CERN", says Van den Brand. "We don't even know what kind of particles and fields are present in those kind of regimes, making it difficult to predict what we'd see", he says. "With this instrument we could take a leap and look, for the first time ever."

As people measure more and more gravitational waves, with new and improved detectors, scientists are standing at the beginning of a new golden era in astronomy, cosmology, and fundamental physics. "Just think", says Van den Brand. "More than a year ago, theoretical physicists were arguing about the true nature of black holes, invoking theoretical ideas like firewalls", he says. "Now they have to be careful. For the first time ever, we can actually see these things, and measure them. The enormous implications of that are now slowly starting to be understood by the rest of the scientific community."

ATLAS

Technician Arnold Rietmeijer working on the ATLAS detector upgrade.

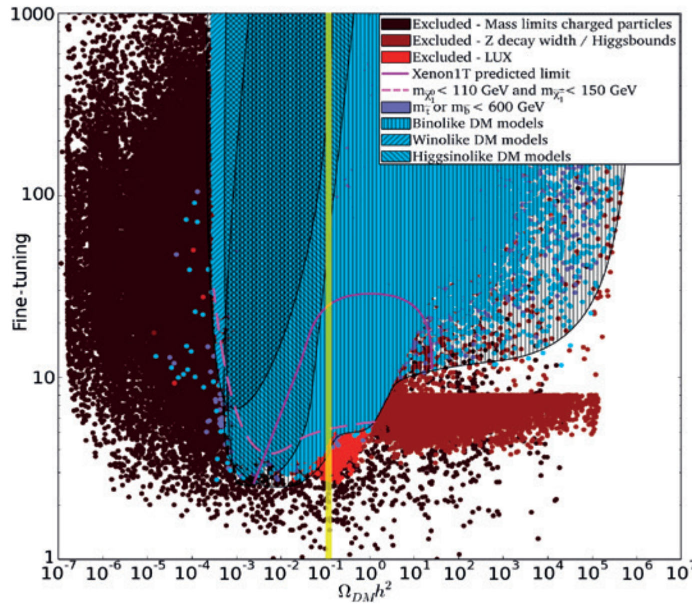


Figure 1.The impact of LHC limits and Dark Matter direct detection experiments on the viability of the Minimal SuperSymmetric extension of the Standard Model. The 19-dimensional parameter space of the model is randomly sampled: MSSM parameter configurations that are excluded by experimental constraints are shown as black/brown/red/purple points. Parameter configurations that are compatible with all experimental constraints are shown in blue. Notably, a sizeable fraction of the MSSM parameter space is not yet excluded even by Run-2 LHC data, including ample configurations that require little parameter fine tuning.

Management
prof.dr. N. de Groot
prof.dr. W. Verkerke

The year 2016 has been a fantastic year for the Large Hadron Collider, with a total luminosity of 39.6 fb^{-1} delivered with a beam energy of 13 TeV, of which 36 fb^{-1} have been recorded by the ATLAS detector. With this massive volume of data in one year of data taking, many measurements and searches now exceed the precision that was obtained in the first run of the LHC (2010–2012).

Precision testing of the Higgs sector

In 2016 the Higgs boson, which was discovered in Run-1, is now being subjected to a variety of precision tests. These tests will ultimately tell if the particle discovered in 2012 is the Standard Model Higgs boson, or (one of the) Higgs particles of larger theory that happens to have somewhat similar properties. Nikhef has played a leading role in many Higgs analyses this year: As a wrap-up of the LHC Run-1 effort, the combined measurement of the Higgs coupling properties by the ATLAS and CMS experiments was finalised into a journal publication. But the focus has been on the analysis of 2016 data: a first combined measurement of Higgs properties using this years Run-2 data from the observation of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ decays was shown at the ICHEP conference in summer 2016. Another new summer result on this year's data was the search for the rare and not-yet-observed production of Higgs bosons in association with top quark decays. The programme of measurements on the discovered Higgs bosons is complemented by a search effort for hypothetical other species of heavier Higgs bosons decaying into vector bosons. These searches have significantly increased their reach in 2016, due to both the larger data volume and increased beam energy. In preparation for the ultimate future precision interpretation of all Higgs boson measurements Nikhef has also contributed to a joint experiment/theory effort, documented in CERN Yellow Report 4, to improve the theoretical modelling Higgs boson property observations: a novel method to construct probability models describing experimental Higgs observations directly from predictions of effective Lagrangian theory models, and a novel method to measure Higgs couplings in polarised vector boson decay.

Searches for new particles

The increased beam energy of 13 TeV of the LHC in Run-2 strongly increases the production rate of hypothetical new heavy particles, boosting their opportunity to be discovered, if they exist, or strengthening limits on their mass, in case they don't exist. The search in this first full year of high-energy data taking is still in the early phase: the search is focused on (comparatively) easy signatures with a large production rate that constitute the 'low hanging fruit' for such searches, and largely focus on the same signature as the searches in the Run-1 data. Nikhef has played a leading role in two of these searches: the search for strongly produced supersymmetric particles in decays without leptons and search for (miniature) quantum black holes decaying into at least two leptons.

Meanwhile, searches for new physics, *e.g.* new fundamental particles, with more challenging experimental signatures are being prepared. These new searches will gain in discovery potential as more data is collected at the LHC in the next years. One of these newly developed searches is the hunt for extremely rare decays of Z bosons and Higgs bosons where lepton flavour is not preserved. A first publication, proving the feasibility of such searches at the LHC on Run-1 data was published in 2016. Another newly developed analysis is the search for experimental decay signatures of dark matter candidates in super-symmetric extensions of the Standard Model that are not ruled out by any existing experimental observation, nor require extensive fine-tuning of the theories parameters to be viable.

Preparing ATLAS for the long term future

In the coming years, the LHC is expected to deliver many more collisions than today. To achieve this, the number of simultaneous collisions per bunch crossing will increase: from about 40 now, to well over 200 in 2025, with a quantum jump expected in 2025 as the high-luminosity upgrade of the LHC is completed. To cope with these future highly complex collisions and with the increased radiation pressure both the inner part of the detector and the readout electronics must be replaced. Nikhef participates in the design and construction of several of these components: We will assemble one of the end-caps of the all-silicon new inner tracker (ITk) at Nikhef. The first phase of the effort, the mechanical design of the end-cap structure was finalised in 2016, with a very significant contribution from Nikhef designers, engineers and physicists. We are also contributing to the design of the new radiation hard readout chip of the ITk pixel sensors, realised in 65 nm technology, through the RD53 collaboration. Nikhef contributes also to the core design of the system of the new FELIX system. FELIX will provide the interfacing of the data acquisition, detector control and timing and control systems to the new muon detectors and first level trigger systems to be installed during the the 2019–2020 LHC shutdown. Deployment of FELIX for all other detectors and trigger systems should follow in the 2023-2025 shutdown. The FELIX system went through an important design review in 2016; and its progress was positively acknowledged. In the first deployment phase, the FELIX system will be rolled as the readout system for the Muon system in 2019–2020 LHC shutdown, with the other detector systems following in the 2023–2025 shutdown. Finally, Nikhef also assisted in the procurement of B-field and temperature sensors for the Muon New Small System that will be installed in 2019.

Figure 3. Participants of the FELIX development workshop of October 2016 at Nikhef.

Convenerships and management positions in the ATLAS experiments

Paul de Jong was chair of the publications committee. Pamela Ferrari and Frank Filthaut were convener of the H→WW physics subgroup. Further coordination positions held by Nikhef members were in the Luminosity Group (David Salek), B-Trigger (Olga Ignonkina), Muon Software (Jochen Meyer), Tracker Alignment (Pierfrancesco Butti) and Data Quality (Pamela Ferrari).

'Shell Afstudeerprijs voor Natuurkunde'

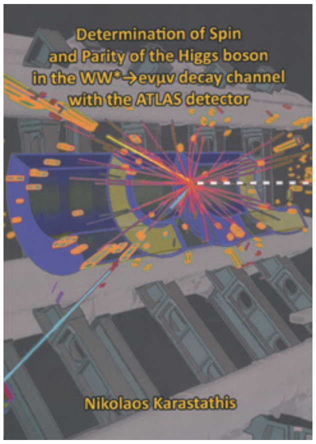
Melissa Beekveld received a *'Shell Afstudeerprijs voor Natuurkunde'* (Shell Graduation Prize for Physics) of the *Koninklijke Hollandsche Maatschappij der Wetenschappen* (KHMW, Royal Holland Society of Sciences) for her master thesis research project on dark matter with ATLAS.


Melissa Beekveld

Wouter Verkerke appointed professor

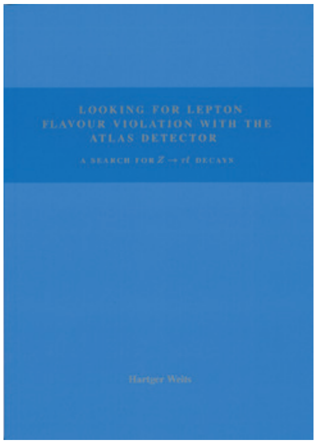
Wouter Verkerke (see photo on p. 13) was appointed special professor of 'Data Analysis in the field of particle physics and astroparticle physics' at the Faculty of Science of the University of Amsterdam. The focus of Wouter Verkerke's research will be on advanced data analysis in particle physics and astroparticle physics, and his teaching activities will also focus on data analysis and computing.

Jörn Mahlstedt
21 January 2016

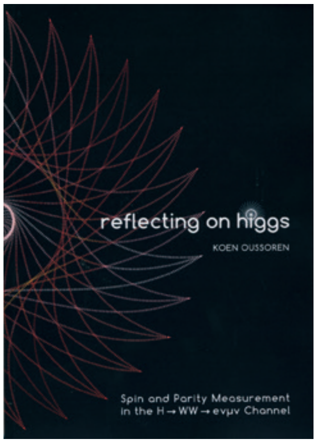


Nikolaos Karastathis
25 February 2016

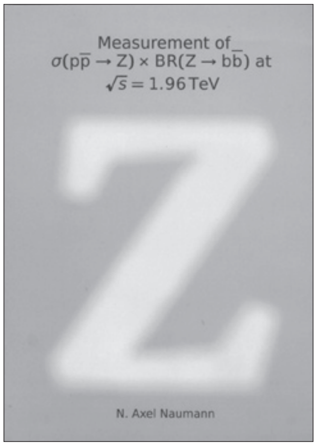
Pieter van der Deijl
16 March 2016



Hartger Weits
21 September 2016



Koen Oussoren
27 September 2016



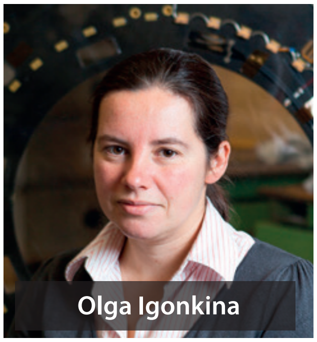
N. Axel Naumann
24 October 2016

Ingrid Deigaard
30 November 2016

Vidi grant Tristan du Pree

Tristan du Pree was awarded a Vidi grant for his proposal “Higgs from Z to A”. The Vidi grants are aimed at young excellent researchers with several years of successful postdoctoral research experience to start their own research groups.
“The Higgs boson was discovered in 2012 by CERN’s Large Hadron Collider. The physicist conducting this research will use the Higgs bosons to make precision measurements to study their characteristics, to search for scalar particles, and to attempt to shed light on dark matter – a new step in particle physics.”

Vici grant Olga Igonkina



NWO granted Olga Igonkina a Vici grant for her proposal “How leptons make the world”. This form of grant is for senior researchers who have shown that they have the ability to successfully develop their own innovative lines of research and to act as coaches for young researchers.
“During the Big Bang matter and antimatter were ‘made’ in equal quantities. So why is it that 13.8 billion years later we see a vast excess of matter and scarcely any antimatter? Particle physicists think that the elementary lepton particle can provide an answer to this fundamental question about the evolution of our universe.”

A few times a year Nikhef director Stan Bentvelsen presents a ‘Spiegelmoment’ with topical information about the institute.

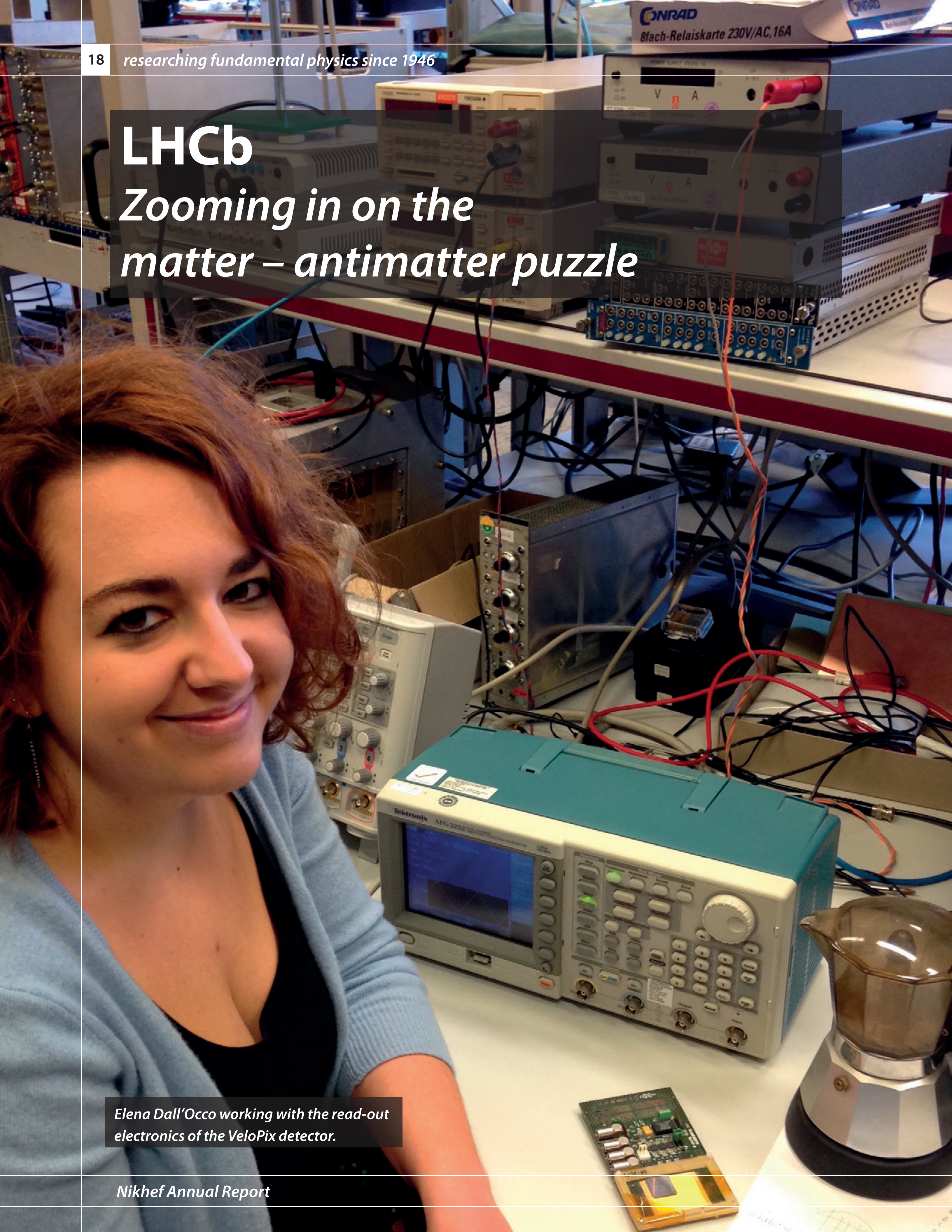
NWO Transition

As of 1 January 2017, FOM has been converted into the institute organization of NWO. The granting part of the FOM bureau went to the NWO domain Exact and Natural Sciences (ENW) and the part that supports the institutes and university groups is transformed into the NWO-institute organisation (NWO-I). Nikhef, together with AMOLF, ARCNL and DIFFER, is now part of the NWO-I organisation per 1 January 2017, the NWO institutes NSCR, NIOZ, ASTRON, CWI and SRON will merge by 1 January 2018.

Illustration of the transition process as used in internal communications.

A new NWO board was installed per 1 January 2017 with as chairman prof.dr. Stan Gielen. In addition, new directors have been appointed for the NWO-I bureau (dr.ir. Christa Hooijer) and the new NWO domains' dr. Dirk Jan den Boer (Social Sciences and Humanities), dr. Arian Steenbruggen (Exact and Natural Sciences) and dr.ir. Herry Nijhuis (Technological and Applied Sciences). These new directors including a representative of the fourth domain (dr.ir. Janna de Boer, Medical Sciences), visited Nikhef on 17 November.

LHCb
Zooming in on the matter – antimatter puzzle



Elena Dall'Occo working with the read-out electronics of the VeloPix detector.

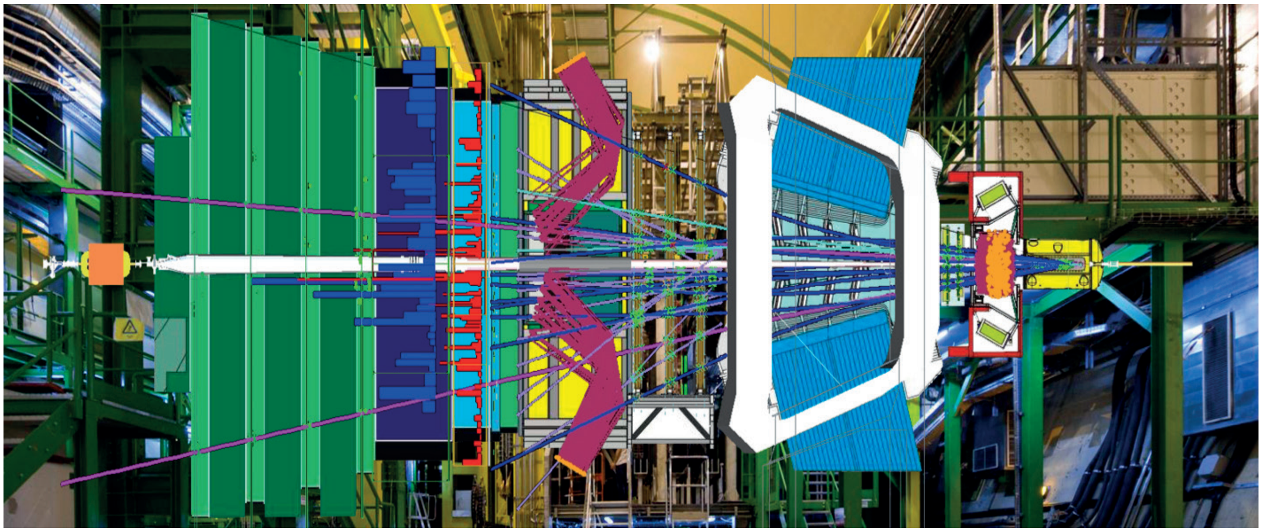


Figure 1. Display of a reconstructed LHCb collision superimposed on the detector in the LHCb hall.

Management
prof.dr. M. Merk

The year 2016 was a year of smooth data taking for the LHCb experiment during which a wealth of data was collected. An example of a reconstructed event is shown in Fig. 1. Whereas in 2015 LHCb attracted the main attention on various observations of so-called 'forbidden decays', the year 2016 saw exciting new results on the topic of CP-violation: the riddle of the asymmetry in the laws of nature between matter and antimatter particles. Members of the Nikhef group were involved in several of these analyses involving transition between beauty particles and antiparticles and their decays.

Matter – antimatter oscillations

Neutral B_d and B_s mesons are particles that consist of an exotic anti b-quark together with a d-quark and an s-quark respectively. Due to virtual quantum processes these mesons have the possibility to change their nature from particle to anti-particle with an extremely high frequency of 80 thousand million Hz for the B_d and 3 million-million Hz for the B_s. Vidi laureate Jeroen van Tilburg together with PhD students Jacco de Vries and Laurent Dufour performed a precision measurement to test whether the transition rate from B_s to anti-B_s particle occurs at a different speed compared to the reverse process from anti-particle to particle. Their results, shown in Fig. 2, demonstrate that these transition rates are identical to a precision of 0.5% and that no CP-violation occurs in this process, in contradiction with a previous, more indirect, measurement of the D0 collaboration.

Matter vs antimatter particle decays

Although no CP violation is observed in the particle–antiparticle oscillation process, Nikhef researcher Niels Tuning and PhD student Lennaert Bel studied an alternative mechanism that involves the quantum processes of oscillation and decay. They chose the decay mode where a neutral B_s particle decays to a D_s particle (c-quark plus anti s-quark) and a Kaon (anti-s quark and u-quark). An intricate quantum interference of direct and indirect decays leads to matter–antimatter differences of the rate at which this process occurs, depending on the time each individual B_s-decay occurs. This process is considered to be a standard reference for the so-called Cabibbo

Kobayashi Maskawa explanation of CP violation. The measurement resulted in the first evidence for the existence of decay-time dependent CP violation for B_s mesons and was presented at the international beauty conference in Marseille.

Antimatter and time reversal symmetry

Proceeding even beyond CP-violation Jeroen van Tilburg together with Nikhef master students Maarten van Veghel and Yorgos Chatzikonstantinidis used B-particles to test the validity of combined CPT symmetry, de facto asking: *are antimatter particles identical to matter particles travelling backwards in time?* They examined whether decays of B-particles might be affected by the direction or magnitude of velocity of the particles in space, in a process called Lorentz symmetry violation. In a beautiful analysis they observed no sidereal effect due to the rotation of the earth and set a limit of Lorentz violating parameters that was a factor of ten better than previous results by the BaBar collaboration.

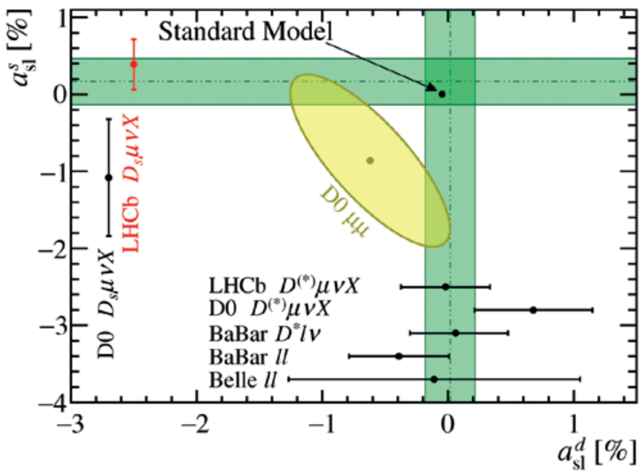


Fig 2. The relative B_s – anti-B_s oscillation asymmetry (vertical axis) and the B_d – anti B_d mesons oscillation asymmetry (horizontal axis). The red data point is the recent measurement of the Nikhef group; in black additional measurements and in yellow the so-called di-muon measurement of the D0 collaboration.

Preparing for the future

Simultaneously to the analyses of data collected with the LHCb experiment the Nikhef group steadily increased their activities toward the construction of the upgraded LHCb experiment. A team of physicists and technicians, under the leadership of Wouter Hulsbergen, designed modules for a novel Si pixel detector and its 'VeloPix' readout electronics. A major milestone was passed by Martin van Beuzekom and Elena Dall'Occo as they demonstrated that the novel pixel detectors together with the new VeloPix chip gave promising results in beam-tests at Cern. Fig. 3 shows the set-up of the experimental area.

A second team lead by Antonio Pellegrino constructed prototypes of modules for the large surface scintillating fiber tracker ('SciFi'). The team successfully managed to complete a challenging prototype of an end-piece of the detector module in which scintillating fibers are read out by Silicon Photomultipliers at a temperature of –50 °C.

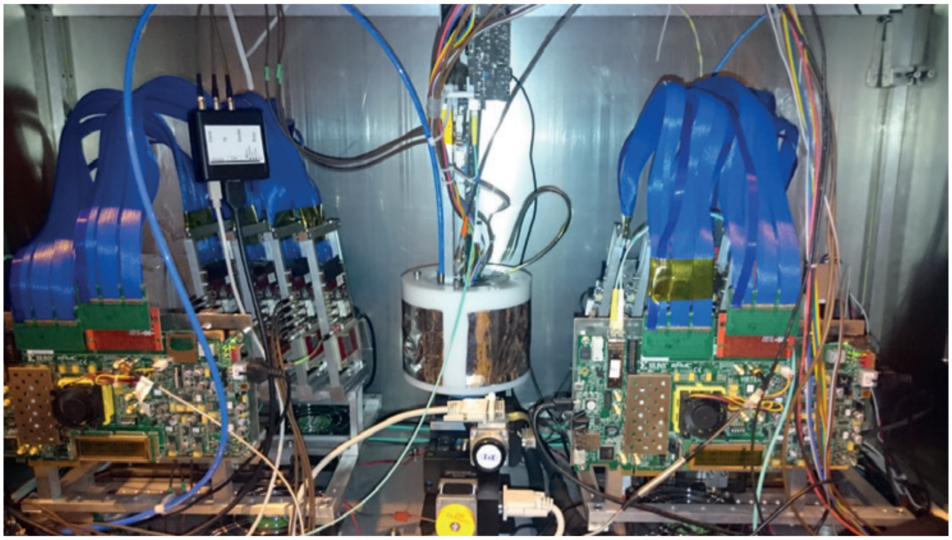
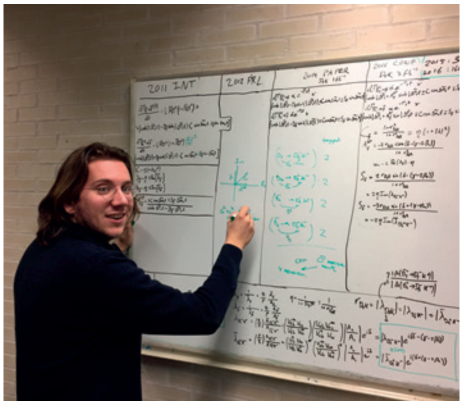


Fig 3. Picture of the beam test telescope at Cern used to test the prototypes of the upgrade Velo pixel modules.

Both the Velo and the SciFi teams are preparing to start the mass-production of detector modules in Nikhef cleanrooms in 2017.

Personal highlight of Lennaert Bel during finalization of angle gamma analysis

"Over the last year-and-a-half I've been working on a measurement of CP violation using the decay process $B_s \rightarrow D_s K$. I started off by sifting through all the LHCb data for this kind of events, as well as producing matching simulated data. Running these operations required immense computing power: I kept numerous computing nodes all across Europe busy, for weeks at a time! The next steps I worked on are a mass fit to properly separate the data from background, as well as a fit to the decay time of the B_s particles. The latter fit requires good knowledge of the accuracy of the decay time, for which I did an extensive study. It's very important to get this right, since it directly affects the measurement of the CP-violating parameters. In the end, we had to ensure that the numbers we got matched the quantities from the theory – as you can see, you need an entire whiteboard to work this out in full detail!"



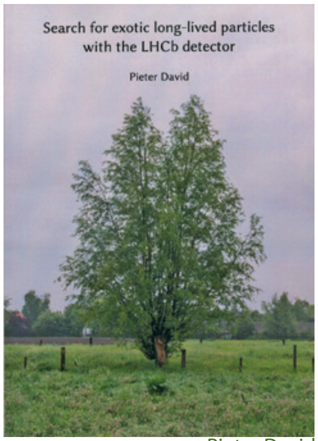
Lennaert Bel cross checking the mechanism of B meson oscillation and decay: was there a mistake with a minus sign?

Personal highlight of Elena Dall'Occo in Velo upgrade beam tests

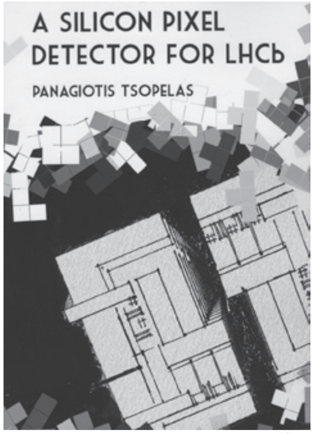
"As a PhD at Nikhef I have the great opportunity to contribute with my work to the upgrade of the LHCb experiment and specifically of the VErtex LOcator (VELO). From my point of view, the sensor characterisation project that I have been working on is a full experiment in its own right. The ultimate goal is to choose out of several prototypes the best sensor for the upgrade experiment, according to a series of beam tests and comparisons of their performance."

"The project allows me to learn how the experiment currently works and how we can improve it in the future. The tests are carried out using a beam of particles at the SPS (CERN) and a dedicated telescope (Timepix3 telescope) for tracking position and timestamp. When I started my PhD the telescope was already built and working beautifully, so I jumped directly in the middle of the operations. Doing shifts for the data taking was the best way for me to approach this new new subject and to see in reality what I had only read about on paper. The testbeam project has been a great and educational experience. Sitting in the control room in front of two screens with your co-shifter for many hours in a row requires more than pushing a button to start and stop the data acquisition. Every set of measurement is planned for a particular analysis and it is our duty to take the required amount of data and check their quality. As in each scientific experiment or analysis, there are always some issues, so it is important not to freak out but think calmly how to deal when problems occur and if you can't solve it by yourself: call the experts."

Jeroen van Leerdam
18 May 2016



Pieter David
7 July 2016



Panagiotis Tsopelas
21 November 2016

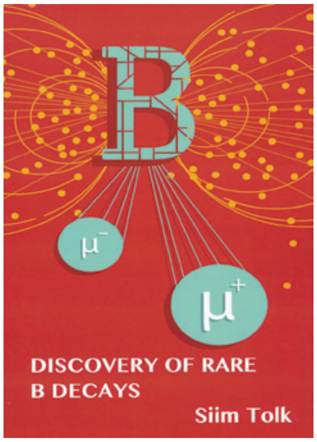
A testbeam involves working together not only with your colleagues, coordinating in the data taking and keeping track of the work done, but also with other groups/users on the same beam line and their needs. Of course being part of a great group of people makes it easier when there is a work related problem, but it is also a nice experience spending many hours together, including pizza/kebab breaks, and drinking litres of coffee to stay awake during the long nights waiting for the beam.

All in all I learnt a lot since I started, I keep learning at every shift and hope to continue in the future.

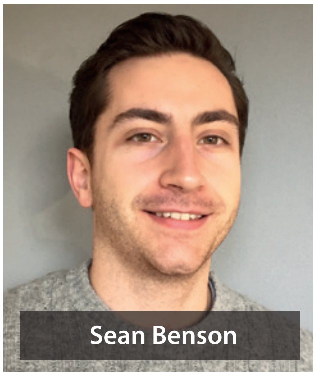
Jan Kluyver Prize Siim Tolk

Siim Tolk received the 2016 Jan Kluyver Prize for the best English summary of a Nikhef PhD thesis. The main result of his thesis with the title *"Discovery of Rare B Decays"* is the first ever observation of B_s meson decays into two muons.

The Jan Kluyver prize was established in 2010 by the Education Committee *(Onderwijscommissie, OWC)* of the Research School Subatomic Physics *(Onderzoeksschool Subatomaire Fysica, OSAF)*. The jury consists of the former directors of Nikhef.



Siim Tolk
8 April 2016



LHCb Early Career Scientist Award

In September 2016, Sean Benson received the 'LHCb Early Career Scientist Award' for his contribution to the High Level Trigger, the so-called Turbo-stream.

Photonic chips: the rise of a new era

Deepak Gajanana
Electronics Technology

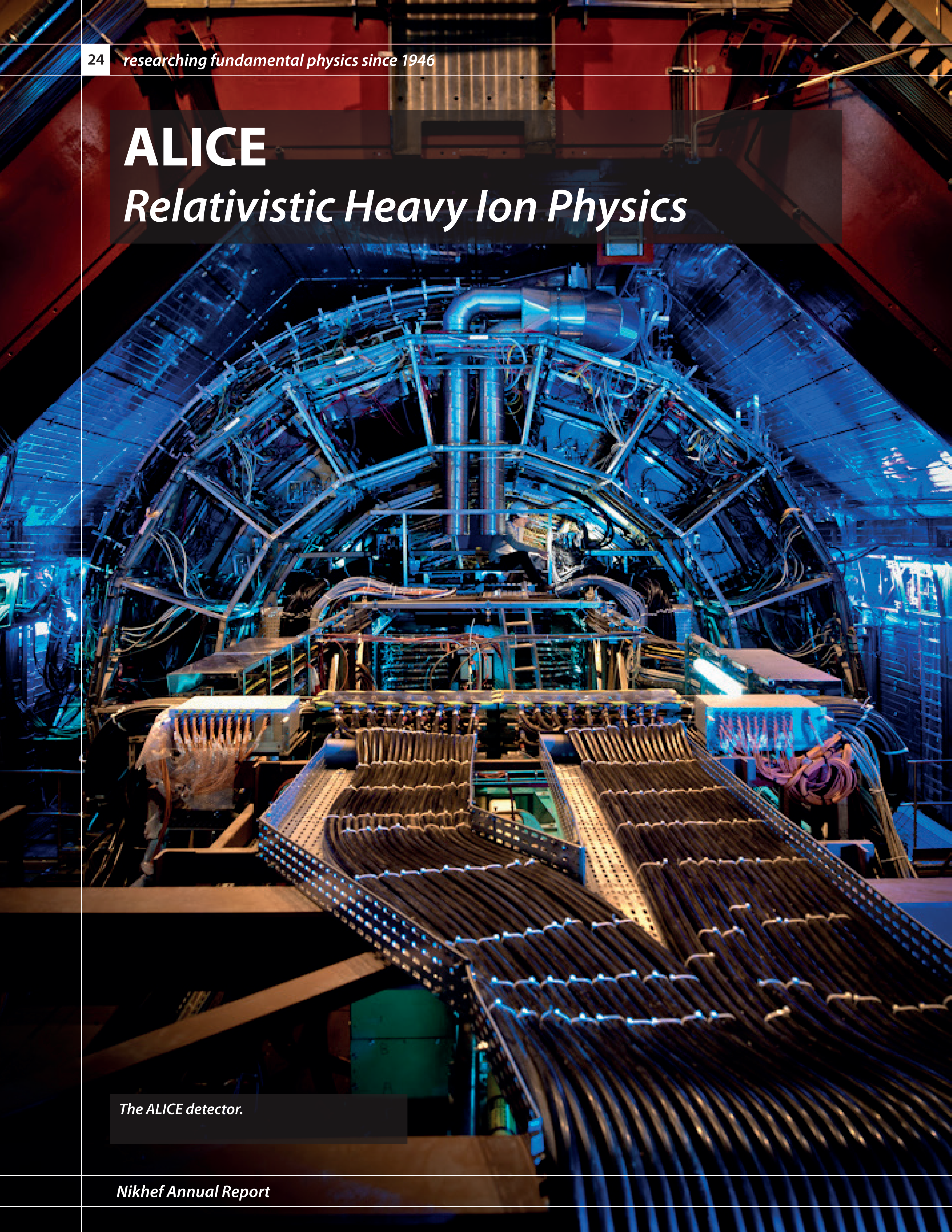
By Laetis Kuipers

Deepak Gajanana is a System-on-Chip Designer with a degree in Electrical Engineering. He works as a Technical Scientist in Nikhef's Electronics Technology Department where, together with colleagues, he is involved in the development of photonic chips. As he explains: "These chips for data transmission are based on the use of light (photons) rather than electrical signals. Photonic chips have huge potential: they can be used in countless devices and mobile equipment. Compared with micro-electronic chips, they are significantly faster and much more energy efficient, especially when it comes to handling amounts of data that are increasing at exponential rates. They are also highly suitable for the development of new applications in a wide range of domains, from healthcare diagnostics to the agro-food industry, to name but two examples."

Over the years, Deepak's area of expertise has developed into a research field of its own. As he puts it: "Rather than operating mainly as support staff, we have now arrived at a point where we conduct deep research ourselves: manipulating light at nano-level is by no means straightforward. Although the development of photonic chips is still in its infancy, the European Framework Programme for Research and Innovation, Horizon 2020, has already identified integrated photonics as a key enabling technology of the twenty-first century. With our research, technical know-how and applications, we can make valuable contributions to Nikhef's other projects and thus to technical innovations and valorisation."

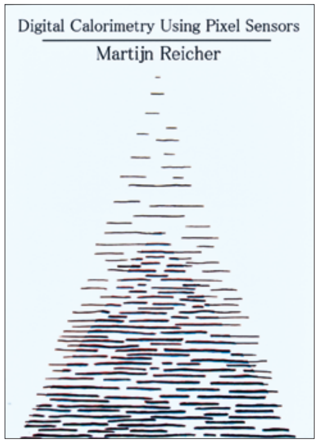
Deepak: "To satisfy my innate curiosity, my thirst for knowledge and my heartfelt wish to operate in a line of technology that has profound effects on society, I gave up my position with a corporate firm and ventured into the realms of research and development. In my new work, I experience a lot of creativity and an abundance of fundamental puzzles waiting to be solved. I am extremely fortunate to be able to combine my work at Nikhef with a PhD position at TU Eindhoven's Photonic Integration Group. I've got the best of both worlds, so to speak. With this combination, I found that there's hardly ever a dull moment. What I find particularly fascinating is that new developments evolve so rapidly. It fills me with gratitude to see that we at Nikhef play an important role in this process."

ALICE
Relativistic Heavy Ion Physics



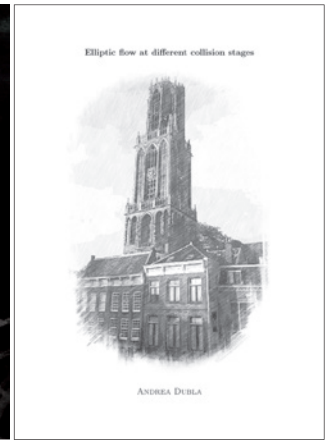
The ALICE detector.

You Zhou
6 January 2016



Martijn Reicher
7 March 2016

Misha Veldhoen
14 March 2016



Andrea Dubla
6 April 2016

Management
prof.dr. R.J.M. Snellings

In the Standard Model of particle physics Quantum Chromodynamics (QCD) predicts, in case the density and/or temperature exceed a critical value, a phase transition from colourless hadronic matter to the so-called Quark Gluon Plasma (QGP), a plasma where the quark and gluon degrees of freedom are not anymore confined. The main goal of the ALICE experiment is to determine the properties of this newly formed hot and dense matter. Furthermore, ALICE is well suited for a precision test of QCD at central and forward rapidity and down to the ~ 0 p_T regime in pp, p–Pb and Pb–Pb collision systems.

Higher flow harmonics in Pb–Pb collisions

In a semi-central Pb–Pb collision (*i.e.* collisions with a large impact parameter), the initial spatial anisotropy of the overlap region between the two nuclei was conjectured to be smooth and almond shaped. The aforementioned conjecture went under scrutiny in the past few years, when experimental measurements and hydrodynamic calculations have pointed out that such region must have an irregular shape originating from the initial random distribution of the gluons and nucleons in the nuclei, which fluctuates from one event to the next.

These event-by-event fluctuations in the initial spatial anisotropy can be investigated by studying the azimuthal correlations between final-state particles relative to the symmetry plane of the system and quantified by a Fourier series of the azimuthal distribution of particle production relative to the aforementioned symmetry plane.

The elliptic-flow coefficient v_2, representing the second harmonic of the Fourier expansion, has been one of the main focus of the heavy-ion community in the last few years. Elliptic-flow measurements, both at RHIC and LHC colliders, contributed to the revelation that the Quark-Gluon-Plasma (QGP) generated in heavy-ion collisions behaves as an almost perfect liquid. The ratio of shear viscosity to entropy density (η), which is a measure of its fluidity, is very close to the lower bound of $\hbar/4\pi k_B$ conjectured by the anti-de-Sitter/conformal field theory (AdS/CFT) correspondence. The higher-order harmonics $v_{n,\, n>2}$, representing modulations to smaller spatial scales, are more sensitive to the value of ηS of the QGP. In addition, since they mainly originate from the initial state and its fluctuations, $v_{n, n>2}$ are a unique tool to constrain them. Furthermore, if studied for different particle species, they can also probe the effect of the dissipative, late-stage hadronic re-scattering on the flow coefficients.

Recently, the ALICE collaboration has used Pb–Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV to measure the elliptic (v_2), triangular (v_3), quadrangular (v_4) and pentagonal (v_5) flow coefficients of π±, K±, p and p̄ for different centrality intervals. For central collisions (0–1%), in which the initial spatial anisotropy is predominantly driven by the initial-state fluctuations, one observes significant non-zero values for all harmonics and particle species (see Fig. 1 for pions).

The v_3 and v_3 coefficients become progressively dominant with increasing transverse momentum, while even v_5 for p_T > 4 GeV/c is comparable to v_2. For more peripheral collisions, v_2 is the dominant flow harmonic. Higher harmonics also have significant nonzero values with a mild dependence on centrality.

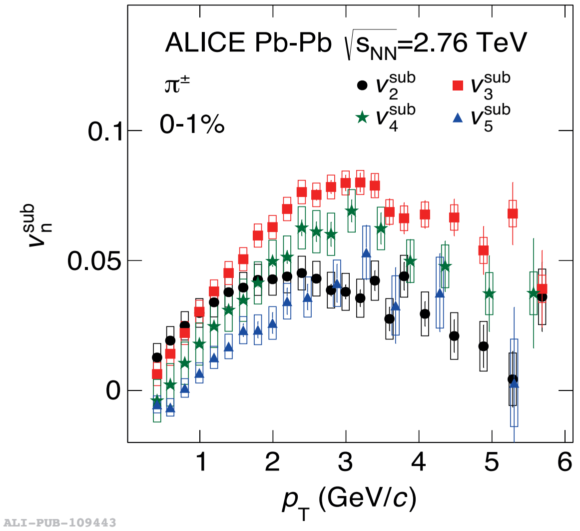


Figure 1. The evolution of the p_T–differential v_n^{sub} for $\pi^\pm$ in 0–1% Pb–Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. The superscript sub stress the removal of non-flow contributions (*i.e.* contributions from jets, resonances and quantum statistics correlations).

While these observations confirm that v_2 is driven mainly by the anisotropy in the collision geometry, the higher harmonics are mainly describing the initial-state fluctuations. Furthermore, comparison with models highlighted the importance of the late hadronic rescattering stage to the development of the observed mass ordering at low values of p_T and of coalescence as a particle production mechanism for the particle type grouping at intermediate values of p_T for all harmonics.

Silicon tracker upgrade

ALICE completed the installation of current detectors during the first long LHC shutdown (LS1) with the aim to accumulate 1 nb^{-1} of Pb–Pb collisions during Run-2 corresponding to about 10 times the Run-1 integrated luminosity. However, to fully exploit the physics opportunities and challenges of LHC Runs 3 and 4, the collaboration is preparing a major upgrade of its apparatus, planned to take place during LS2, in the years 2018–2019. At present, the ALICE Time Projection Chamber (TPC) readout rate is about 0.5 kHz for Pb–Pb collisions. After the upgrade the TPC will be able to record all Pb–Pb interactions at a rate of ~50 kHz. In addition a new, high-resolution, low-material budget Inner Tracking System (ITS) will improve the tracking precision significantly (see Fig. 2).

These new detectors in combination with upgraded data acquisition, will allow ALICE collecting about $10 nb^{-1} Pb–Pb minimum-bias interactions in the period 2019–2021. This sample represents an increase by a factor of one hundred with respect to the Run-2 collected statistics.

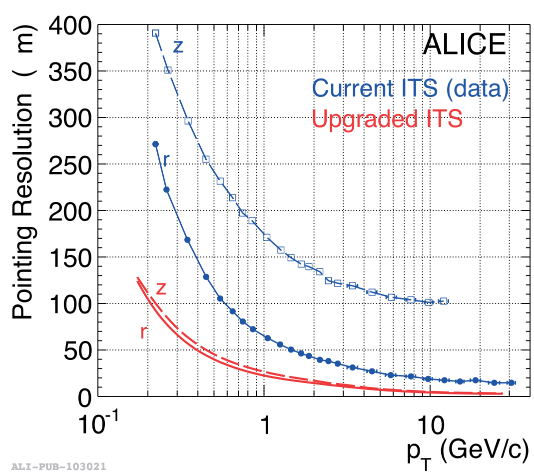


Figure 2. Comparison of the r–φ and z resolutions between the current ITS (blue) and the upgraded ITS (red).

The Nikhef ALICE group holds a major role in the upgrade of the ITS detector. The group had an important role in studying the physics performances of the ungraded detector for D and B mesons studies and, through simulations of the geometry of the upgraded detector, is contributing to the development of the new alignments tools that will be used during commissioning phase. Furthermore, the Nikhef group is responsible for the read-out board, which controls the front-end pixel modules and sends the pixel data to the data acquisition system. This board will also integrate the power regulators for the pixel modules. Since the read-out board will be located at a few meters from the interaction point it will be designed for full compatibility with the magnetic field and the radiation environment. The main task of our group during the production of the ITS will be the assembly staves from individual pixel modules. The assembly involves many steps. Each module will be tested at each step during the assembly procedure.

During 2016 the tools required to test and manipulate the modules were successfully developed (see Fig. 3). Our group will distribute these tools and the testing software among the stave assembly sites.

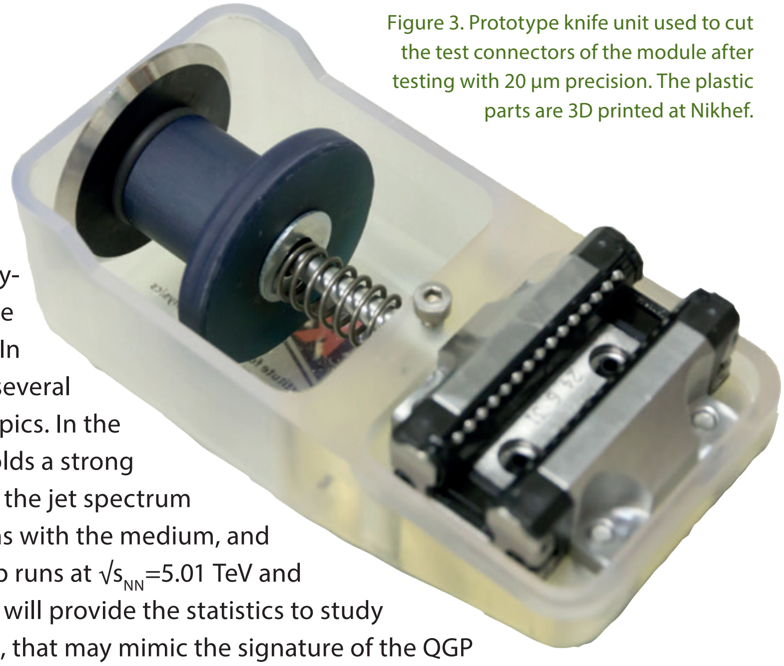
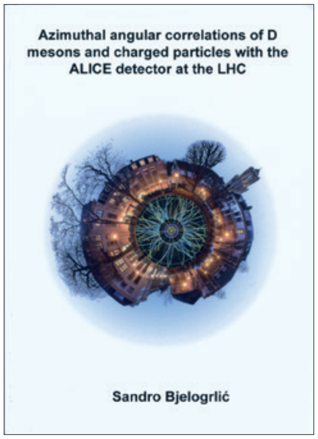


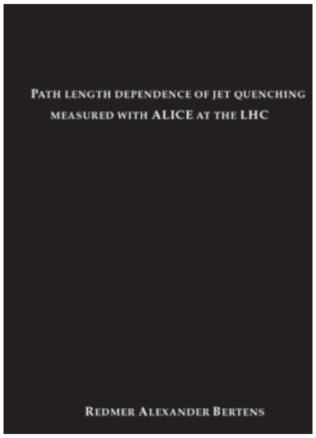
Figure 3. Prototype knife unit used to cut the test connectors of the module after testing with 20 μm precision. The plastic parts are 3D printed at Nikhef.

Outlook

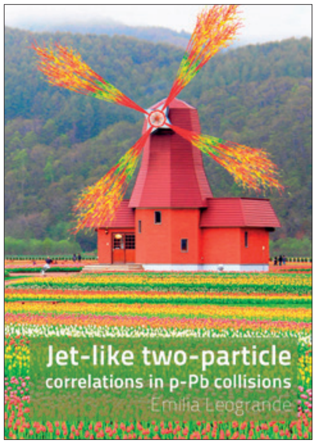
The highlights presented here are a selected summary of results from ALICE in which the Nikhef group played a main role. For the flow higher harmonic measurement, a next step is to study them by using Pb–Pb collisions collected in 2015 that will allow placing more stringent limits on η/s and the initial conditions of a heavy-ion collision. For the ITS upgrade activities the 2017 will be a focal year for the assembly and testing of the modules. In addition to what reported here, our group is involved in several other correlation measurements that address different topics. In the area of hard probes and parton energy loss, the group holds a strong role in heavy-flavour measurements, in measurements of the jet spectrum and modifications of jet fragmentation due to interactions with the medium, and in the measurement of real and virtual photons. The p–Pb runs at $\sqrt{s_{NN}}$=5.01 TeV and $\sqrt{s_{NN}}$=8 TeV collected in November-December of this year will provide the statistics to study in detail the initial state effects, as shadowing and Cronin, that may mimic the signature of the QGP in Pb–Pb collisions.



Sandro Bjelogrlić
4 May 2016

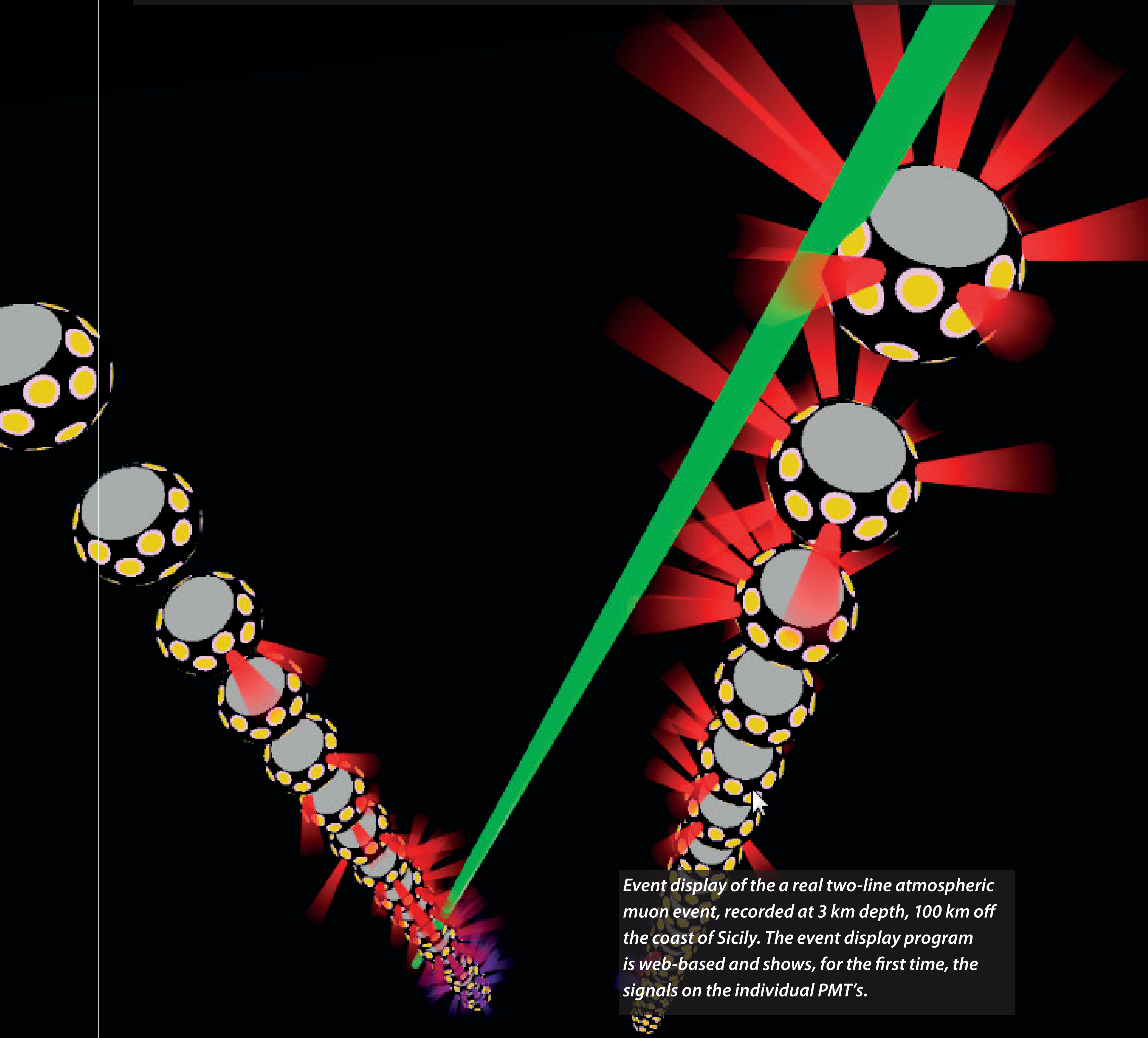


Redmer Alexander Bertens
31 October 2016



Emilia Leogrande
7 December 2016

KM3NeT
Constructing the next generation neutrino telescope



Event display of the a real two-line atmospheric muon event, recorded at 3 km depth, 100 km off the coast of Sicily. The event display program is web-based and shows, for the first time, the signals on the individual PMT's.

Nikhef technician Rene de Boer is assembling one of the DOMs that soon will be lowered in the Mediterranean Sea.

Management
dr. A. Heijboer

Nikhef is heavily involved the construction of the next generation neutrino telescope in the Mediterranean Sea: KM3NeT. We have led the development of the chosen technology at both the conceptual and technical levels. This cost effective technology is a major asset of the project. An example is the Multi-PMT optical module, which offers more information per detected Cherenkov photon, and a better price per unit sensor area compared to earlier options. A novel deployment mechanism developed by NIOZ and Nikhef allows for multiple lines to be deployed safely in a single sea campaign, which is essential for deploying the hundreds of lines that will make up KM3NeT. We are also involved in optical module production, mechanics and optical-network efforts. In February 2017 Maarten de Jong's double term as spokesperson of the collaboration ends. Els Koffeman and Aart Heijboer have been elected to be part of the new management team in the role of technical coordinator and deputy spokesperson respectively.

Among the science goals are establishing the neutrino mass ordering and the discovery of the sources of cosmic neutrinos observed by IceCube a few years ago. New hints on mass hierarchy and even CP violation of neutrinos are coming in from Nova and T2K. KM3NeT will yield a particularly sensitive determination of the mass ordering in case the large mixing angle θ23 is in the second quadrant and the mass ordering is 'normal'; a scenario that is fully compatible with the latest data. Furthermore, other neutrino oscillation physics can be done, such as a measurement of the octant of θ23, looking for non-standard interactions, and testing unitarily using nu-tau appearance.

With the discovery of cosmic neutrinos by IceCube, it has become very clear that neutrino astronomy not only requires the ability to detect muon-neutrinos. The capability to accurately measure the other two types, electron- and tau-neutrinos, is a crucial asset. The reconstruction software for this is another key contribution of our group. KM3NeT will measure the origin of cosmic neutrinos in the sky with an accuracy that is an order of magnitude better than our present knowledge from

IceCube. This leads to an image of the neutrino sky with a factor 100 more 'pixels', which greatly enhances the capacity to correlate the neutrinos to the many potential neutrino sources that are known from radio and gamma-ray observations. While identifying and studying the astrophysical sources of the cosmic neutrinos is currently a major goal in astroparticle physics, cosmic neutrinos also provide a free 'beam' to study the fundamental particle physics at energies three orders of magnitude higher than with terrestrial beam experiments. They can be used to probe several scenarios of physics beyond the standard model, which would lead to a detectable imprint on the neutrino flavour ratios detected on Earth.

Ongoing Detector construction

In December 2015, the first line has been deployed at 3.5 km depth, and connected via a pre-installed 100 km long electro-optical cable to the shore station in Porto Palo, Sicily. The first detection line, which was constructed in the Nikhef workshop, has been taking data in Mediterranean sea for over a year now. In May 2016, two more lines have been deployed. One of these has since been recovered due to an electrical problem, which has since

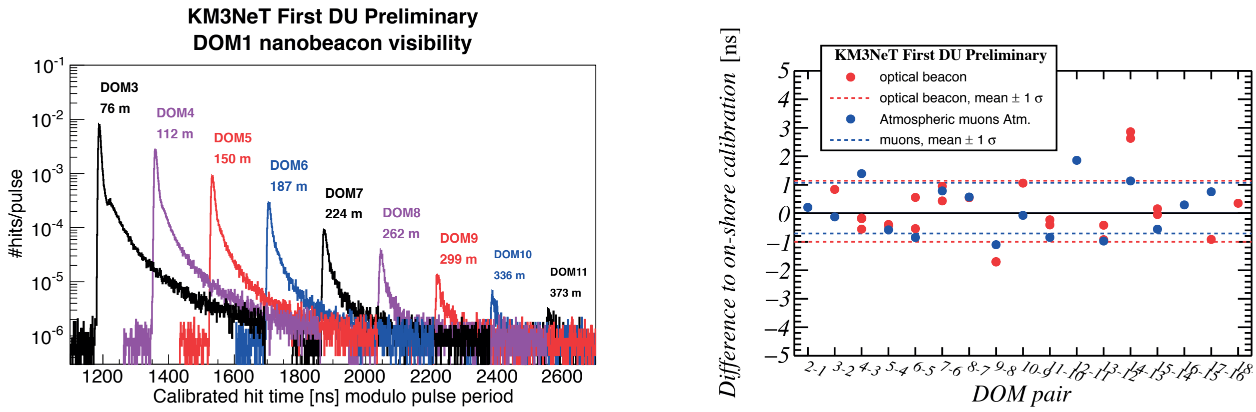
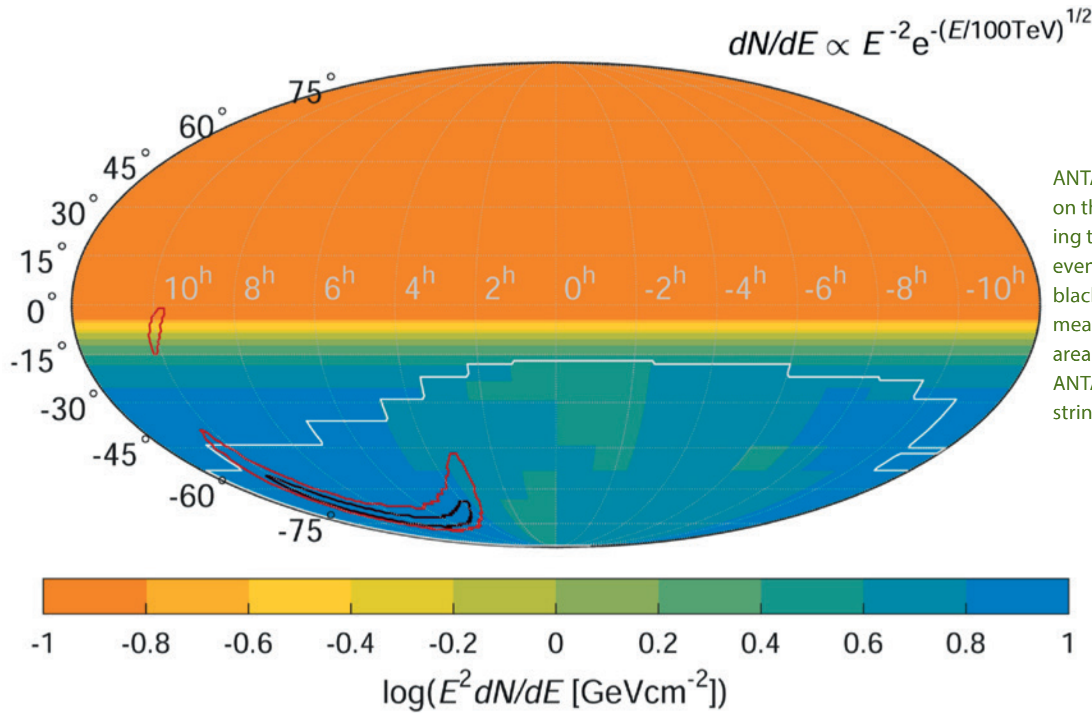


Figure 2. Left: Calibration signals: an optical beacon is flashed and the signal observed over a large part of the detection line. A precise measurement of the arrival time of the light is used to check the detector's timing calibration. Right: comparison timing offsets from optical beacon analysis and an analysis using muon tracks with the calibration from the lab; all analyses agree within ~1 ns.

been investigated and understood in the Nikhef workshop. The line will be redeployed after refurbishment. In the meantime, the two remaining detection lines have yielded a wealth of information on the timing performance, allowing the verification of the time calibration system that was developed at Nikhef. The timing accuracy has been verified with optical flashers as well as signals that will eventually become the background to cosmic neutrinos, like 40K decays and atmospheric muons; see Fig. 2.

Production of the digital optical modules (DOMs), see Fig. 3, is progressing steadily. Collaboration-wide the DOM production is led by Nikhef postdoc Daan van Eijk, while Ronald Bruijn in responsible for the local coordination. Production of modules has reached 155 – most of them at Nikhef. The other four production across Europe have also started production.

Figure 3. The components for a KM3NeT optical module. This picture first appeared in an article about KM3NeT in *Nederlands Tijdschrift voor Natuurkunde*.



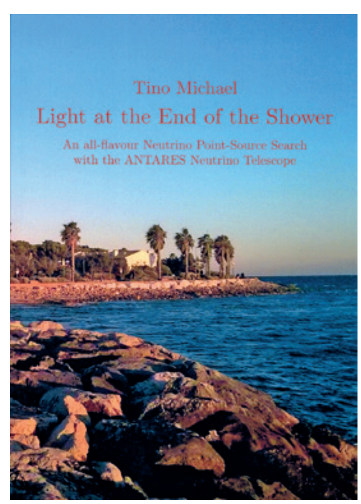
ANTARES and IceCube joint limit on the neutrino flux accompanying the first gravitational wave event GW150914. The red and black contours show the position measured by LIGO/VIRGO; the area below the white line is where ANTARES provides the most stringent limit.

Together, they are scheduled to complete the modules for the first phase of the project. DOM production has so far only been limited by the supply of components, which testifies to the skill of the Nikhef workshop, as well as the efficacy of our design.

Antares

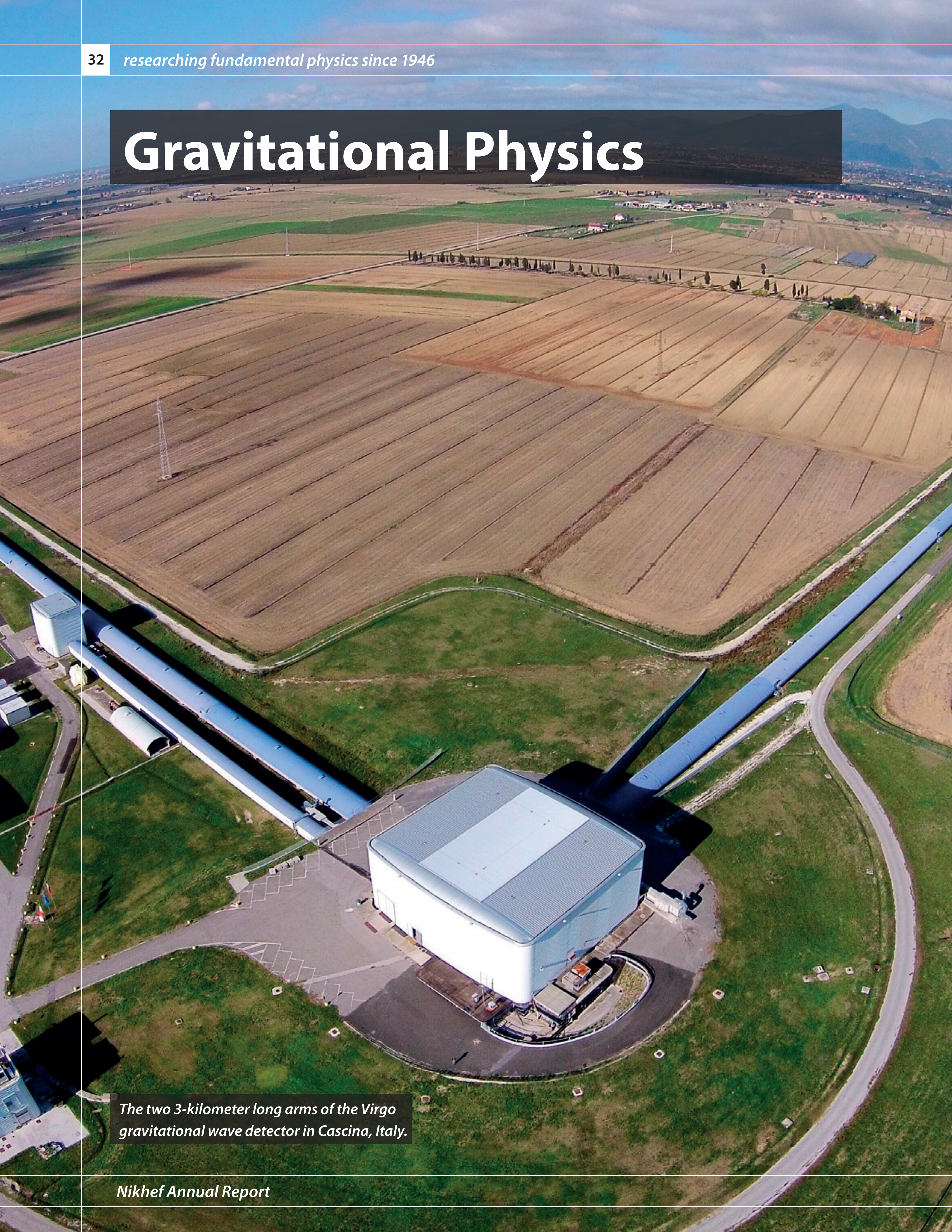
While building KM3NeT takes most of our time, our group still harvests the results from earlier efforts in ANTARES, which has been taking data since 2007. ANTARES has been providing competitive results on neutrino astronomy and indirect dark matter searches. Dorothea Samtleben coordinates the point source analysis and has been involved in many of the key publications. A reconstruction for cascade events with high angular resolution, as developed at Nikhef in 2015, is now an established ingredient in many of the new analyses that are expanding the sensitivity to all neutrino flavours. Using nine years of data the world-best limits on high energy neutrino emission in the Southern sky were set. The cascade events were also included in a new analysis of the Galactic plane based on the likelihood framework as developed at Nikhef. The new limit is by now only 20% above the most optimistic models, and almost identical to the IceCube limits. Despite the small size of ANTARES, these results clearly illustrate the power of a water-based detector in the Northern Hemisphere. For both analyses the combination of Antares and IceCube data is underway.

ANTARES has a broad multi-messenger program, where the neutrino data are compared to optical, radio and gamma-ray measurements. When high energy neutrinos are measured, real time alerts are distributed for fast optical follow up. In similar spirit, the spectacular discovery of the first gravitational wave event by LIGO/VIRGO was followed up by a fast analysis of the neutrino data in both ANTARES and IceCube. As the event concerned a merger of two bare black holes, no neutrinos were expected, which was confirmed by the data. The unique, joint publication by the three collaborations provides limits on the neutrino flux.

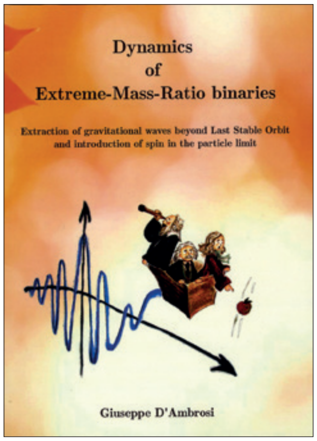


Tino Michael
13 May 2016

Gravitational Physics



The two 3-kilometer long arms of the Virgo gravitational wave detector in Cascina, Italy.



Giuseppe D'Ambrosi
21 April 2016

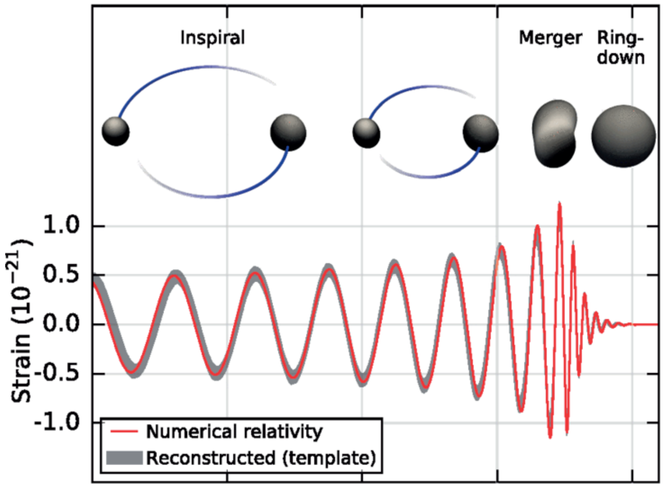


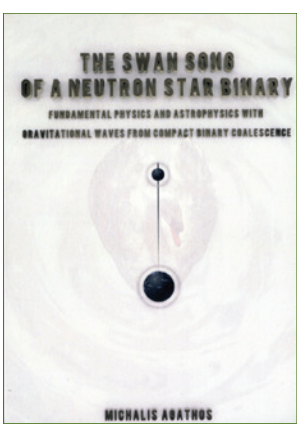
Figure 1: Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce.

Management
prof.dr. J. van den Brand

The first direct detection of gravitational waves (GWs) with LIGO happened on 14 September 2015, and was named 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, respectively; 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, respectively.

Data analysis

The Nikhef group played an important role in the analyses, in a variety of ways. Jo van den Brand was a member of the Detection Committee, 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. Chris Van Den Broeck was Virgo Data Analysis Coordinator, in which role he helped organise 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, Gijs 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.



Michalis Agathos
20 December 2016

GW150914 was what is known as a 'golden event', meaning one whose total mass was such that the merger occurred at a frequency where the detectors are the most sensitive. The process whereby two black holes coalesce is illustrated in Fig. 1. 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

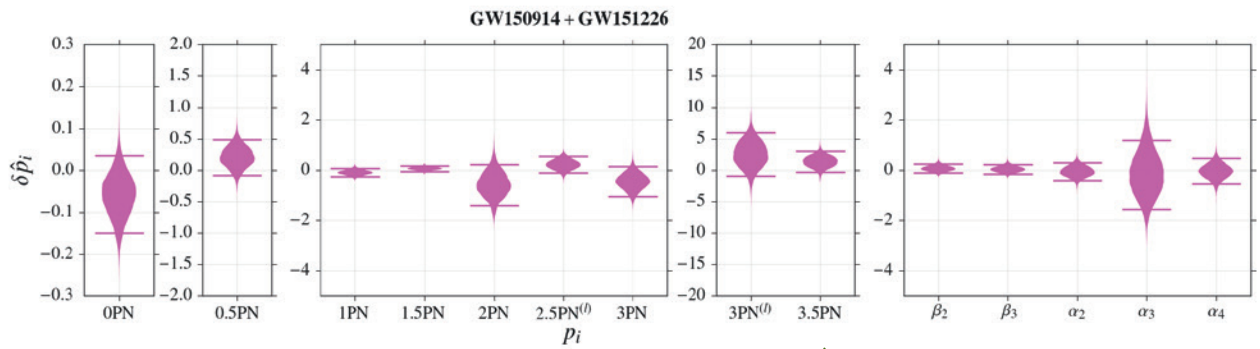


Figure 2: Posterior density distributions and 90% credible intervals for relative deviations $\delta\hat{p}_i$ in the PN parameters p_i (where l denotes the logarithmic correction), as well as intermediate parameters β_i and merger-ringdown parameters α_i. The figure shows combined posteriors from GW150914 and GW151226.

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 Jeroen Meidam; see also Fig. 2.

Another Nikhef result (by PhD student Michalis Agathos) was a bound on the mass of the 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: $m_g < 1.2 \times 10^{-22}$ eV/c^2, the first ultra-high precision result to come from gravitational wave astrophysics. 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.

Meanwhile the group is looking towards the future. It seems likely that binary neutron star coalescences will be detected in the next few years. During late inspiral, the tidal field from one star will induce deformation in the other, which affects the orbital motion; this in turn gets imprinted upon the GW signal and can be measured. How deformable a neutron star will be, is set by the equation of state, which is the main open problem in nuclear astrophysics: theoretical predictions for pressure as a function of density vary by as much as an order of magnitude. As had already been shown before by the Nikhef group in simulations, the observation of multiple binary neutron coalescences will allow us to distinguish between a stiff, intermediate, and soft equation of state.

In 2016, this research moved from proof-of-principle to more practical considerations. Though theoreticians are providing increasingly accurate waveforms with inclusion of tidal effects, these are too slow to generate on a computer, and in pure form are not yet useful in data analysis. A solution is reduced order modelling, a waveform decomposition which retains most of the physics and discards the rest, with a loss of accuracy that is much smaller than the measurement uncertainty. As shown by Nikhef researchers, this reduces the time needed to perform an analysis from more than a year to a couple of weeks, rendering the problem computationally feasible. The same technique will also be needed in tests of GR with binary black holes; it is plausible that O(100) binary black hole coalescences will be observed in the next few years, which would again strain our computational resources.

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

Apart from binary coalescences, fast-spinning, single neutron stars with small deformations (in the order of 0.1 mm) can also be sources of detectable gravitational waves. These are weak but long-duration signals, allowing for long integration times so that they can be extracted from the data. Detecting such radiation would yield additional information about neutron stars, notably the structure of the crust. Many neutron stars will be part of a binary system, where the other component is an ordinary star. The binary motion causes Doppler modulation in what would otherwise have been a monochromatic signal, which considerably complicates the data analysis. To address this, the Nikhef group has been developing *Polynomial Search*, whose computer code is now mature, and can produce upper limits on signal strengths in case of non-detection. An all-sky search on data from LIGO's first science run is in preparation.

Instrumentation 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.

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 those 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 aimed shot noise figure. A complex adaptive optics system, called Thermal Compensation System (TCS), has therefore been realised for Virgo, based on different types of wavefront sensors and non-contacting thermal actuators, to statically and dynamically correct the aberrations.

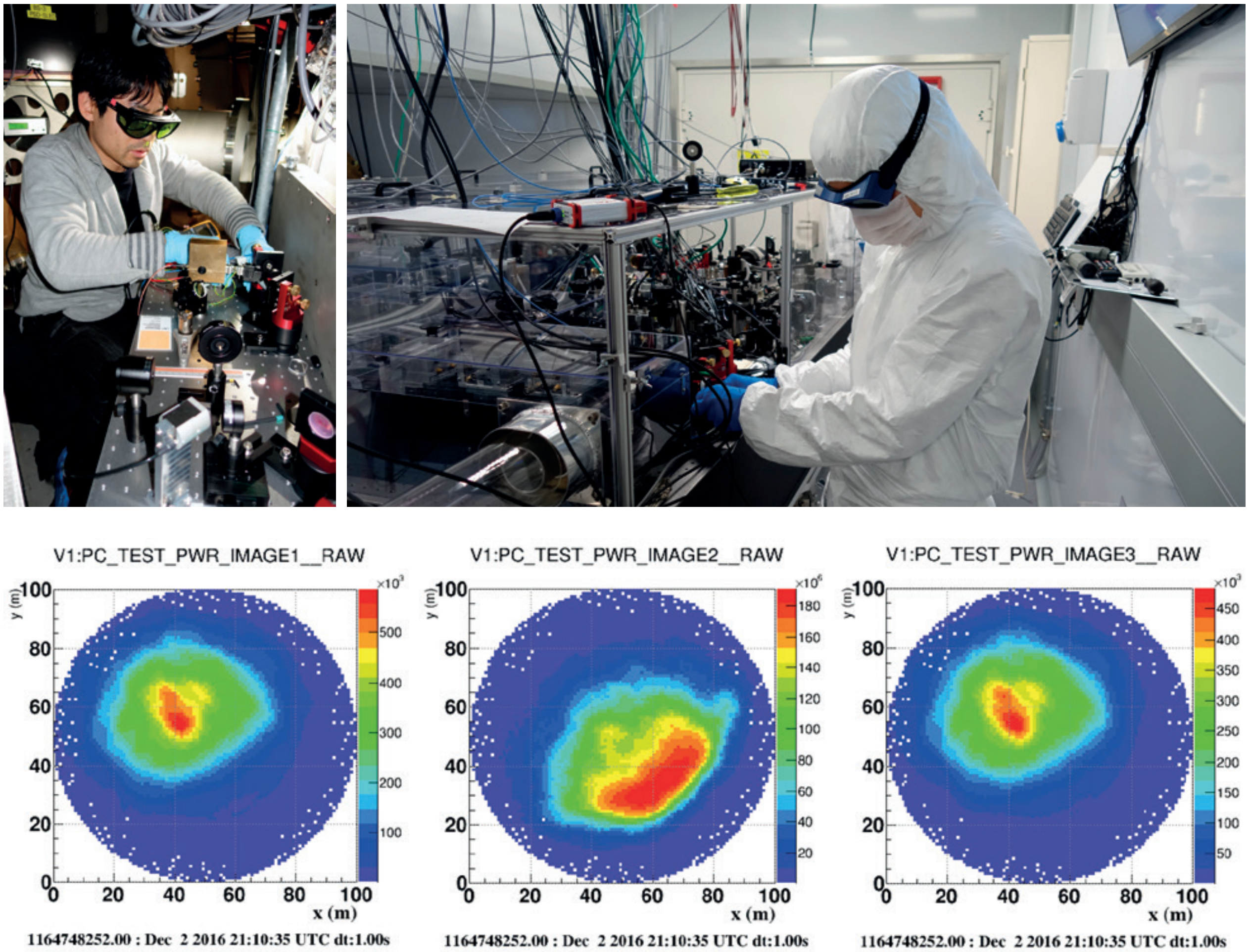


Figure 3: Top left panel: Kazuhiro Agatsuma (postdoc) installing the phase camera PC2 at the power recycling cavity pick-off port. Top right panel: Laura van der Schaaf (PhD student) installing the reference phase camera in the Laser Room. Bottom panel: PRC beam intensity profiles as measured by PC2 with PRC locked; the scan shows from left to right the 6 MHz lower sideband, the carrier and the 6 MHz upper sideband.

Among the TCS wavefront sensors, the most peculiar ones are the three Phase Cameras developed and realised at Nikhef which allow to compare, with sub-nanometer 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 (see an example in Fig. 3).

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 6,000 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.

While the full commissioning phase of Advanced Virgo has started, with the initial goal of participating with the two Advanced LIGO detectors in the first joint Observation Run in April 2017, a mid-term further upgrade of the interferometer has been planned. Besides the addition of a frequency independent squeezer for the reduction of the quantum noise, a Newtonian noise cancellation system will be implemented. Newtonian noise, caused by seismic noise inducing mass density fluctuations in the surroundings of the detector test masses, cannot be shielded and can only be mitigated by subtraction techniques by using the measured seismic fields as input. Nikhef is deeply involved in this endeavour which can be considered a pathfinding experiment for such a technology towards the third generation detectors such as Einstein Telescope. In this framework, on August 2016 a Nikhef team has made a survey of the Virgo area to characterise the seismic environment of the detector. An array of cable-less, autonomous seismic sensors, developed by the institute spin-off company InnoSeis B.V., was deployed and the local main seismic noise sources were investigated; the seismic wave propagation characteristics of the area were measured and, by means of inversion algorithms a soil density profile was reconstructed. The gained knowledge is now being used to estimate, through elastodynamic based simulations, the Newtonian noise level of the detector site, and will be used to design the sensor array for the cancellation system.

Still related to Newtonian noise, even if more projected towards Einstein Telescope, is the development of novel MEMS-based seismic sensors that incorporate Nikhef proprietary technology. Large arrays of several thousands of ultralow noise seismic sensors will be needed in third generation gravitational wave detectors for the suppression of Newtonian noise. For this reason, MEMS technology, suitable for cost effective large scale manufacturing, is very attractive. Several sensor prototypes have been produced in collaboration with the MESA+ laboratory of Twente University and nano-g level resolutions, suitable for these applications, have been achieved in the Nikhef laboratory by using conventional discrete components conditioning electronics. Since the fall of 2016 the design of a companion ASIC has been started with the aim of further improving the resolution, reducing the form factor, and lowering production cost and power consumption.


Michalis Agathos

Rubicon grant Michalis Agathos

Michalis Agathos obtained funding in the framework of the Rubicon programme of NWO for his proposal *"Exploring Gravity With Gravitational Waves"*. For a period of 24 months, he will conduct research at the University of Cambridge. With Rubicon, NWO creates an opportunity for scientist who have recently gained their PhD to acquire research experience at internationally renowned institutes abroad. *"The recent discovery of gravitational waves marks the kick-off for a new era of physics. The researcher will combine state-of-the-art methods to test general relativity and alternative theories of gravity against signals detected from colliding black holes and neutron stars."*

Dutch-German impulse for gravitational wave research

In April 2016, Nikhef and the German Albert-Einstein Institute (AEI) signed a declaration in the presence of Dutch Prime Minister Mark Rutte to strengthen scientific and technological cooperation in the area of gravitational wave research. The signing took place during the Hannover Messe 2016, the world's largest technology trade fair. Nikhef and AEI intend to develop a joint vision on new (third generation) detectors for gravitational waves. One of the most promising projects is the Einstein Telescope. Joint research into a possible location for a future detector in Europe will form a key part of the cooperation. One of the ways this takes place is in the form of feasibility studies, looking at sites in the Dutch-German border area in South-Limburg and North Rhine-Westphalia.

Mark Beker
Innoseis

Mark Beker, director of Innoseis, founded the company together with Jo van den Brand in 2013 as a Nikhef spin-off. Before that, he had completed his PhD at Nikhef on gravitational wave detector research, for which he received the FOM valorisation chapter prize in 2014.

"Nikhef has been very important for our start-up in establishing relations with industry. Cooperation between the institute, industry and the start-up produces synergy. Nikhef offers networking, knowledge and credibility. Shell offers industrial knowledge and finances. The start-up is the source of innovation."

"We produce seismic detectors that are smaller, lighter and cheaper than our competitors'. From the start, there has been a long-standing collaboration with Shell. They bought a hundred of our sensors and use them for testing their geophysical models. Moreover, we work together with an oil and gas company in Eastern Europe that has borrowed a network of sensors for tests. In the end, we would like to develop networks of over 100,000 sensors that will really enable us to look underground."

"Another use of the sensors is in the detection of earthquakes. Moreover, we are also discussing their use with defense and police authorities; they would like to be able to tell whether someone walks in certain areas. Also the location of explosions could be determined by the sensors."

"Finally, the work on the sensors can also have a strong feedback on the work for gravitational wave detectors."

Eric Hennes
Mechanical Technology

By Laetis Kuipers

As a Physics Engineer in Nikhef's Mechanical Technology Department, Eric Hennes is closely involved in the development of various technical-mechanical instruments for the European gravitational wave detector Virgo. "My specialty lies in vibration isolation," he explains, "a technique that enables us to prevent 'noise' from being measured together with relevant signals. We do this by damping environmental vibrations and seismic movements that interfere with the detection of gravitational waves. To achieve this, our team at Nikhef has developed the suspension of six auxiliary optical systems that previously were directly connected to the ground. It's one of Virgo's improvements that were needed to reach the required sensitivity of 'Advanced' Virgo. And now we are waiting for this system to become operational in a few months' time."

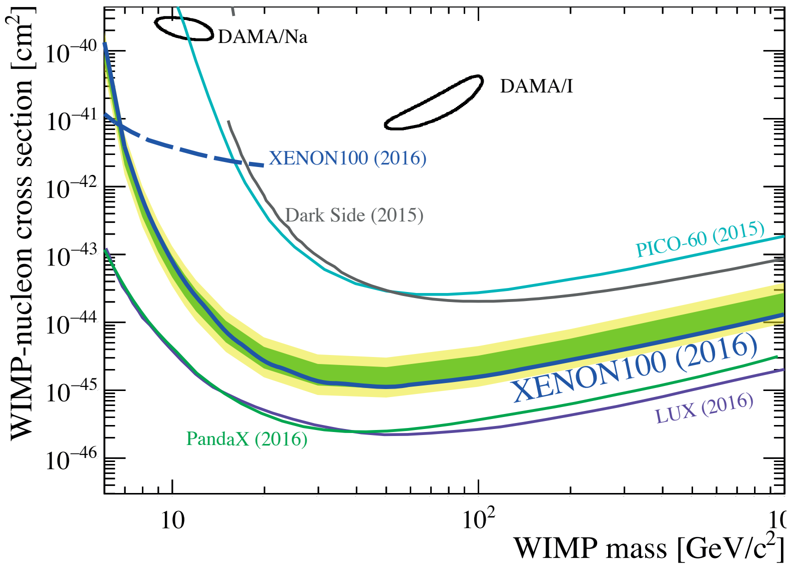
"I must say," Eric continues, "that I can hardly wait for the moment when, together with our colleagues from LIGO and Virgo, we will measure new events. Something that we hope to see is gravitational waves from the merging of neutron stars. What makes our work in this field so very exciting is that it signals the beginning of a completely new type of astronomy. We currently have two LIGO detectors in the USA that have captured gravitational waves, but imagine how much more we could see when we have three detectors. We can then use triangular measurements to determine the location of the sources of the gravitational waves. And with Virgo upgraded to the best possible standards, I expect the new constellation to work significantly better, perhaps even ten times better. This surely is a prospect to relish."

"Physics has always been my passion, and next to my work in the Mechanical Technology Department I am closely involved in Nikhef's outreach projects. I worked in academic education for much of my earlier professional career, and I very much like sharing my knowledge and experience with others. My main drive for the coming years is the development of the Einstein Telescope (ET), Virgo's large-scale underground successor. Following the first detections of gravitational waves, the realisation of this telescope has come a step closer. Nikhef is heavily involved in ET, particularly in its site selection, presently focused on the province of Limburg. As you can see: there are many more future prospects to relish."

Dark Matter Experiments
XENON1T

Nikhef Dark Matter staff members Auke-Pieter Colijn, Patrick Decowski, and postdoc Chris Tunnell in front of the XENON1T detector at the underground laboratory LNGS in Italy.

Figure 1. The dark matter landscape before the start of XENON1T. The lines show the present limits for the WIMP-nucleon cross section as a function of WIMP mass for different experiments. The solid blue line is the final result from XENON100 and the dashed blue line shows the XENON100 result for the low-mass WIMP analysis led by Nikhef. XENON1T will have an ultimate sensitivity reach of 1.6×10^{-47} cm^2 at 50 GeV/c^2, *i.e.* below the scale shown on the y-axis.



Management
prof.dr.P. Decowski

The main Nikhef Dark Matter group activity was the preparation for the scientific run of the XENON1T experiment. Construction of the detector was completed at the end of 2015 and most of 2016 was devoted to commissioning of the subsystems and calibration of the detector. The first XENON1T dark matter science run started at the end of 2016. While these activities were ongoing, we also analysed data from the XENON1T predecessor, XENON100. The XENON collaboration has also commenced the design of the future XENONnT detector, an upgrade of XENON1T.

XENON1T: Starting the Dark Matter Science Run

The XENON1T detector (see Fig. 1), with 3.5 tons of liquid xenon, has become the world's most sensitive running direct detection dark matter experiment. Most of 2016 was devoted to commissioning the subsystems, calibrating the detector and purifying xenon. The cryostat with the time-projection chamber (TPC), hanging in the middle of a 10-meter diameter water tank, was filled with liquid xenon in April and has remained full of xenon since. Nevertheless, a number of operations still had to be done inside the water tank, which shields the detector from external radioactivity and acts as a water Cherenkov muon veto. The water tank was finally filled in July and the muon veto system commissioned. The fall was spent performing calibrations, with radioactive sources deployed into the water tank but outside of the cryostat (*e.g.* with ^{228}Th and neutrons) and using internal sources, with short-lived isotopes ^{83m}Kr and ^{220}Rn mixed into the liquid xenon. These calibrations were necessary to fully characterise the detector. Simultaneously, we also purified the detector by circulating liquid xenon through the getter and distillation systems. The getter system removes electronegative impurities and improved the electron lifetime from 1 µs to about 500 µs, sufficient for the first dark matter run. The distillation system was used to remove the isotope ^{85}Kr from the liquid xenon, and reducing it by roughly three orders of magnitude. This decreased the ^{85}Kr background contribution to the dark matter search from being the largest background to being almost negligible. All these activities were necessary to prepare XENON1T for the dark matter science run. The dark matter run started at the end of December.

The Nikhef group was heavily involved with almost all aspects of XENON1T commissioning. The flexibility of the Nikhef-designed trigger and event-building system allowed adjustments throughout the year to adapt to changing detector conditions. We also spent a significant effort improving the XENON1T data reconstruction software that also originated in our group and is now the official data reconstruction software of the collaboration. To support the analysis and the adoption of our reconstruction, we organised two collaboration-wide analysis workshops. All these efforts put the Nikhef group in an excellent position to play a leading role in the analysis of the first XENON1T dark matter data.

XENON100: Final Data Analysis

While the commissioning of XENON1T was ongoing, the collaboration also finalised the analysis of the scientific data from XENON100. The Nikhef team led an analysis focusing on low-mass weakly interacting massive particles (WIMPs) by looking only at the charge-related signal ('S2-only'), allowing for a lower energy threshold. This provides better sensitivity than the main WIMP search analysis technique below 8 GeV/c^2 WIMP mass. The other two significant XENON100 analyses were the combination of all three dark matter science runs to obtain the final XENON100 WIMP exclusion plot (see Fig. 1) and a search for annual modulations of the dark matter signal spanning more than four years. We anticipate a few more publications from XENON100, especially on various R&D efforts related to XENON1T and calibrations.

After eight years of almost continuous operation, XENON100 was turned off in July 2016 and the 160 kg of xenon recuperated.

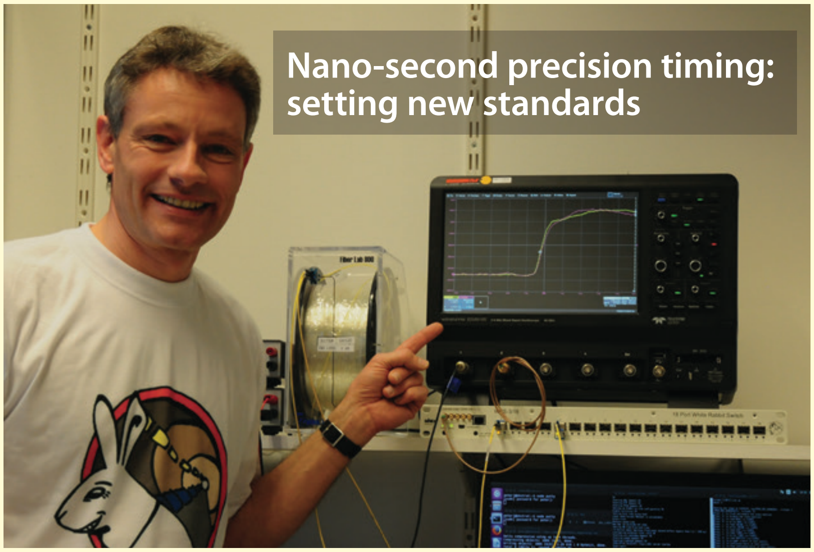
Future Experiments: XENONnT and DARWIN

Even though the scientific exploitation of XENON1T only started, the Nikhef dark matter group is already planning future experiments. The XENON collaboration aims to upgrade XENON1T to about 8 tons of xenon, with a commensurately larger cryostat, time-projection chamber and more photomultiplier tubes. This phase of the experiment is called XENONnT. Most of the other XENON1T infrastructure will remain, and in fact has been designed with the XENONnT upgrade in mind. With the larger xenon target mass and lower backgrounds, XENONnT will have ten times better sensitivity than XENON1T. Installation in the XENON1T water tank is planned for 2019, after XENON1T reaches its final sensitivity. The collaboration has already purchased a large fraction of the additional xenon required.

We also continued studying the 'ultimate' dark matter detector, DARWIN with 50 tons of xenon. This detector, to be operational in 2025, will cover the remaining sensitivity space, up to the point when neutrinos from the Sun and the atmosphere become a difficult to reduce background. Apart from operating as the ultimate dark matter detector, the large xenon mass and extremely low backgrounds would also allow the study of a wide-range of other physics topics. Our group contributed to a long publication summarizing the DARWIN physics programme.

Auke Pieter Colijn appointed professor

Auke Pieter Colijn was appointed special professor of 'Experimental Astroparticle Physics' at the Institute for Subatomic Physics of the University Utrecht with effect from 1 November 2016. Colijn is researcher in the Dark Matter group at Nikhef.



Nano-second precision timing: setting new standards

Peter Jansweijer
Electronics Technology

By Laetis Kuipers

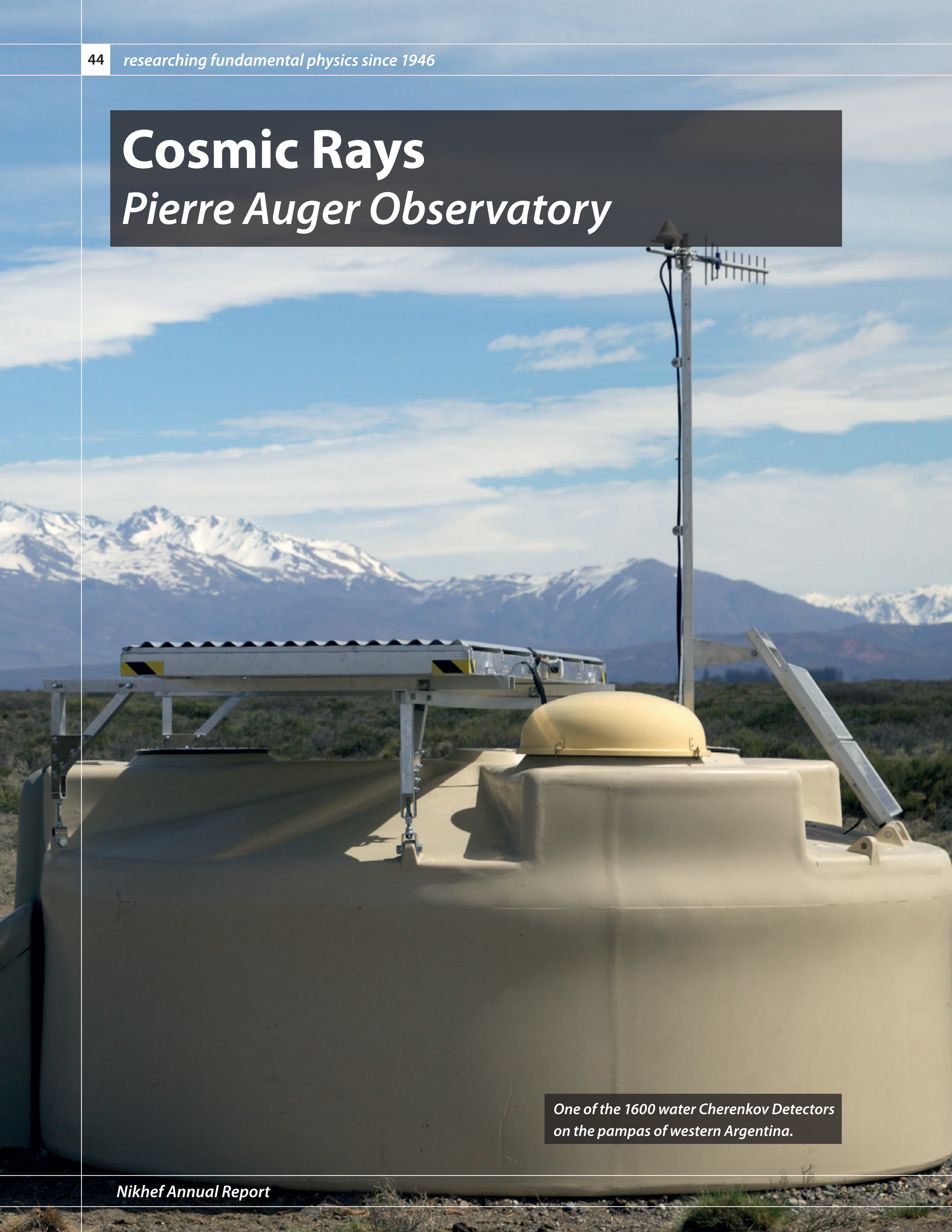
Peter Jansweijer's tasks as an Electronics Engineer in Nikhef's Electronics Technology Department involve pioneering work on the design of a high-precision timing system, developed and applied within the framework of the White Rabbit and KM3NeT projects in which Nikhef participates. Peter: "White Rabbit is an extension to Ethernet-based networks, adding timing synchronisation to general purpose data transfer. Constructed in open collaboration, it enables us to synchronise more than 1,000 devices with sub-nanosecond resolution. We have implemented our timing system in KM3NeT, a next-generation neutrino telescope located in the deepest parts of the Mediterranean Sea. The system we designed is also used at CERN and GSI Darmstadt, and at Nikhef we are responsible for making time-deterministic connections, which means that the time it takes for a message to travel over this connection is known."

"Personally, as an engineer," says Peter, "I very much like working in a bottom-up manner when developing new systems. Others like working top-down, and together we can achieve great things. We now have a stable working system, but there is room for improvement, especially when precision timing systems are applied in domains other than physics, varying from metrology, global positioning and telecommunications to power grids or the development of self-driving cars, to mention but a few. I think it's fair to say that interest in timing systems is booming. The ninth White Rabbit workshop we hosted at Nikhef in 2016 was attended by no fewer than sixty-six participants representing thirty universities and companies in nine countries worldwide."

"In my line of business," Peter continues, "it's easy to stay motivated and committed. I can truly call my work my hobby, one that I share with others with a passion for precision timing. After all, for innovations to be realised and new standards to be set, a great many experts need to join forces. I believe that since 2008, when collaborations first started, we have invested at least one hundred man-years worth of work. That said, one of the achievements that I'm particularly proud of concerns our work in standardisation.

Standardisation is of key importance for widespread future applications, and we're planning to submit final recommendations for new timing system standards in 2018. And there's more to be done, for instance with respect to calibration and self-sustainability. I am really eager to tackle these challenges. It may sound strange, coming from a precision timing expert, but it would seem that time is actually too short."

Cosmic Rays
Pierre Auger Observatory



One of the 1600 water Cherenkov Detectors on the pampas of western Argentina.

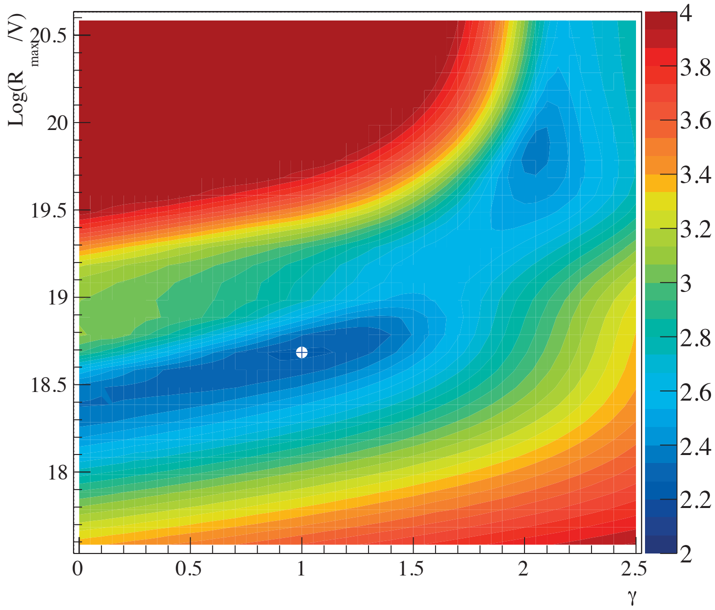


Figure 1. Fit to Auger ultra-high-energy cosmic ray data with models as a function of the model parameters injection index γ and maximum rigidity R_{max}. The fit quality ranges from good in blue to very bad in red. The two best, equally likely fit positions correspond to a normal injection index spectrum with high rigidity cut-off, which is the GZK scenario, and a hard injection spectrum with low rigidity cut-off, which corresponds to a maximum attainable energy of the cosmic accelerators.

Management
prof.dr. S. de Jong

Ultra-high-energy cosmic rays are the most energetic particles we know, exceeding the LHC energy by many orders of magnitude. Yet we neither know their sources, the physics that is needed to generate them, nor the physics that governs their interactions with the air in our atmosphere. The Pierre Auger Observatory was built to resolve these mysteries. It is the world's largest cosmic ray observatory located on 3000 km^2 near Malargüe in the province of Mendoza in Argentina.

The origin of ultra-high-energy cosmic rays

The Pierre Auger Collaboration had already definitively shown that the energy spectrum of cosmic rays exhibits a sharp drop around 10^{20} eV. This drop is compatible with the Greisen-Zatsepin-Kuz'min (GZK) cut-off, above which ultra-high-energy cosmic rays interact with photons of the 2.7 °K cosmic microwave background and will loose their energy when traveling over inter-galactic distances. Due to the different interactions strengths with the cosmic microwave background, the end of the spectrum is expected to be dominated by protons.

However, another reason for the cut-off of the spectrum can be that there is a maximum energy that can be reached by the cosmic accelerators. In that case a heavy composition is expected. Recently, the Pierre Auger Collaboration confirmed a mixed mass composition at energies one order of magnitude below the cut-off energy, *i.e.* at $10^{18.5}$–10^{19} eV.

A more elaborate fit of all available information for ultra-high-energy cosmic rays is shown in Fig. 1, which shows that the two scenarios are about equally likely given the available data.

The AugerPrime upgrade of the Pierre Auger Observatory is aimed at an event-by-event determination of the cosmic ray composition up to the highest energy. This will clearly distinguish between the two presented scenarios. The Nikhef group is strongly involved in the design and production of the SSD modules. The Nikhef group is also a main drivers of the novel technique of radio detection of cosmic rays in the Pierre Auger Observatory.

AugerPrime

The Auger Surface Detector consists of about 1,660 water Cherenkov tanks of 12 ton water each. These tanks are spaced by 1.5 km to cover a surface of 3,000 km^2 in total. When high-energy particles at the end of the air showers pass through the water they make Cherenkov radiation that is observed by three photomultipliers that look down in the water of the tank. For ultra-high-energy cosmic rays, many tanks are hit. The particle flux in a collection of tanks is fit as a lateral density profile and its normalisation renders the energy of the incoming cosmic ray. Depending on the direction of the incoming cosmic ray, the water tanks are hit at different times by the air shower front. From timing reconstruction the arrival direction of the incoming cosmic ray can be determined.

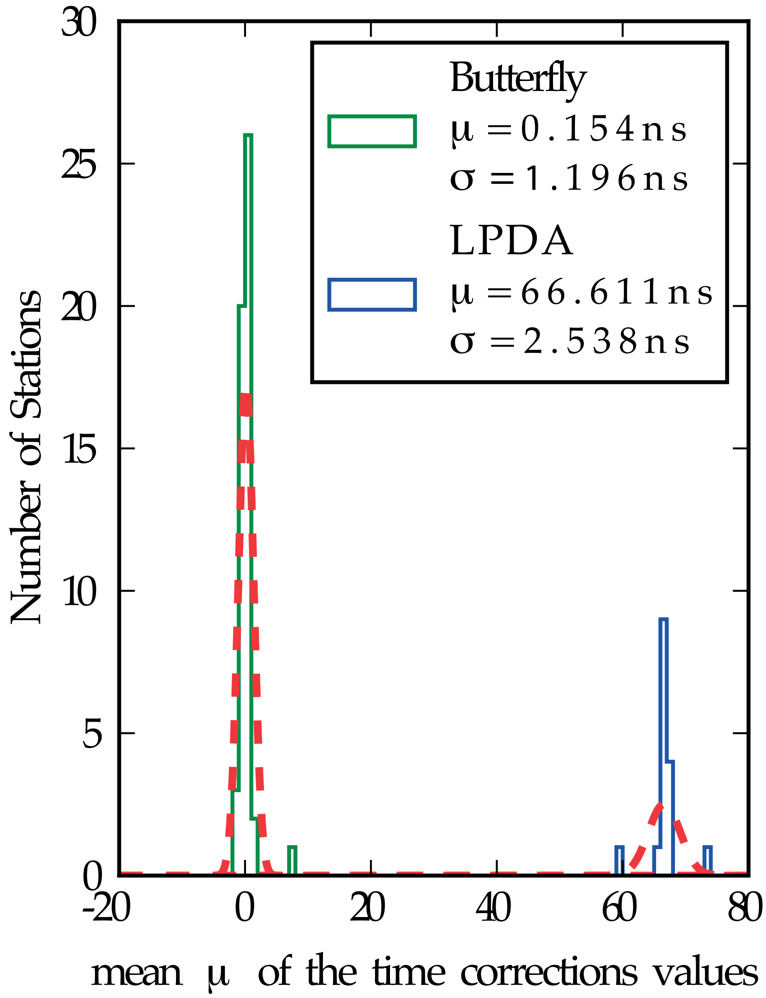


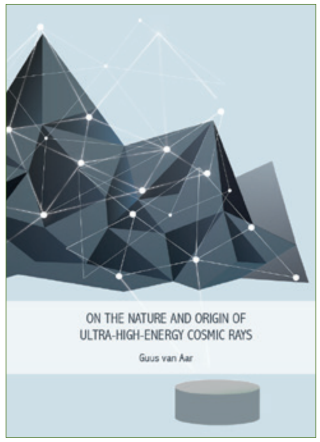
Figure 2. Histogram of the mean μ of the time correction values. The standard deviations σ of the distributions provide a measure for the average agreement between the beacon and airplane methods. The values stated in the statistics box are from fitted Gaussians (dashed lines).

At the same energy light and heavy cosmic ray particles have different interactions with the atmosphere. Light particles, in extremum protons, have a smaller cross section with air molecules than heavy elements, such as nitrogen or even iron nuclei. Therefore, light cosmic rays have the development of their shower deeper into the atmosphere than heavier nuclei. Moreover, the interactions with heavier cosmic rays invoke a more rapid shower development than with lighter ones. In addition, heavier elements tend to produce significantly more muons, especially also at the early stage of the shower, than light cosmic rays.

The AugerPrime upgrade aims at

- elucidating the mass composition and the origin of the flux suppression at the highest energies, *i.e.* the differentiation between the energy loss effects due to propagation, and the maximum energy of particles injected by astrophysical sources;
- searching for a flux contribution of protons up to the highest energies, with a sensitivity down to less than a 10% proton fraction. This is a decisive ingredient for estimating the physics potential of existing and future cosmic ray, neutrino, and gamma-ray detectors. It will predict the flux of secondary gamma-rays and neutrinos due to proton energy loss processes; and
- studying extensive air showers and hadronic multiparticle production at energies beyond those accessible at man-made accelerators, and the derivation of constraints on new physics phenomena, such as Lorentz invariance violation or extra dimensions.

Stefan Jansen
13 April 2016



Guus van der Aar
19 October 2016

These goals will be achieved by

- A complementary measurement of the shower particles will be provided by Surface Scintillator Detectors (SSD) above the existing Water-Cherenkov Detectors (WCD). This allows the sampling of the shower particles with two detectors having different responses to muons and electromagnetic particles and thereby being able to measure these components separately;
- A surface detector electronics upgrade (SDEU) that will process both WCD and SSD signals. Use of the new electronics also aims to increase the data quality (with faster sampling of ADC traces, better timing accuracy, increased dynamic range), to enhance the local trigger and processing capabilities (with a more powerful local station processor and FPGA) and to improve calibration and monitoring capabilities of the surface detector stations;
- An Underground Muon Detector (UMD) in the existing SD infill area of 23.5 km^2. The UMD will provide important direct measurements of the shower muon content and its time structure, while serving as verification and fine-tuning of the methods used to extract muon information with the SSD and WCD measurements; and
- a changed operation mode of the Fluorescence Detector (FD) to extend measurements into periods with higher night sky background, to allow an increase in the current 15% FD duty cycle to over 20%.

The biggest and most important part of the AugerPrime upgrade are the Scintillating Surface Detector modules that will be installed on top of the existing Surface Detector tanks. Nikhef has designed the mounting frame for these modules and is an important partner in designing the modules. A production of a substantial number of SSD modules is planned at Nikhef to start in the second half of 2017.

Progress in radio detection of Cosmic Rays

In 2016 a proof of principle for the timing calibration of the radio detector stations was demonstrated (see Fig. 2). The calibration was based on the use of a beacon, while it was verified using commercial airplanes that flew over the AERA set-up and emitted pulses in the right frequency range for detection by the AERA stations. The timing precision could thus be verified to be about 1 ns for the butterfly antennas and about 2 ns for the Log Periodic Dipole Antennas. Such a precision corresponds in principle to a pointing accuracy of much less than one degree for cosmic rays that are measured by the radio detector.

The VSI for Particle Physics and Gravity and Nikhef

"By the adherence of the Van Swinderen Institute Nikhef strengthens and broadens its scientific portfolio. After already working together successfully for years this signature confirms the intensive cooperation. In particular, the Groningen activities fit seamlessly with our current activities in theory and in experimental research at LHCb. Nationally we have to join forces to make a difference internationally."

— Stan Bentvelsen (director Nikhef)

The year 2016 was an exciting year for the new Van Swinderen Institute (shortly VSI), the youngest partner of Nikhef. For those who did not attend the 2016 Nikhef Annual Meeting in Groningen in December: the Van Swinderen Institute is a fusion between the former Centre for Theoretical Physics *(Centrum voor Theoretische Natuurkunde, CTN)* and the Fundamental Interactions and Symmetries (shortly FIS) and theory groups of the former Nuclear Physics Institute *(Kernfysisch Versneller Instituut, KVI)*. After a lengthy process, the VSI became an official member of Nikhef on 19 February 2016. This joyful event was accompanied by a press release highlighting the scientific interactions between Nikhef and the VSI. The VSI experimental program, focused on low-energy precision experiments, has now become part of the Nikhef research programme. The new Nikhef collaboration also strengthens the already existing ties with the LHCb programme.

Eric Bergshoeff
Van Swinderen Institute, University of Groningen

The mission of the Van Swinderen Institute fits well within the Nikhef partnership and can be summarised as follows: The aim is to study the fundamental forces of Nature and the implications for our Universe. These investigations connect through close similarities in physics from Planck-scale physics (quantum gravity) via subatomic and atomic scales (particle physics, precision measurements) to cosmic dimensions (cosmology). There are both theoretical and experimental efforts that overlap significantly in the search for new physics beyond the Standard Model.

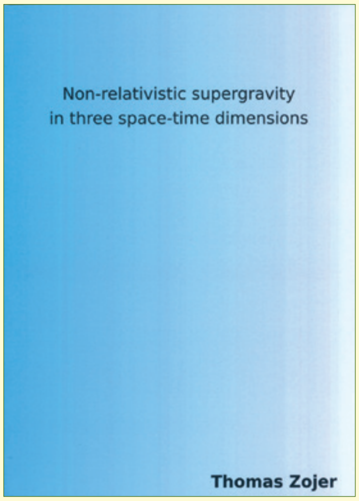
In 2016, the VSI has been successful in attracting two national grants, so-called *FOM vrije programma's*. The first is the experimental eEDM programme Probing Teravolt Physics with Cold Molecules with Steven Hoekstra as Principal Investigator (PI). The second is the theoretical programme Scanning New Horizons: Emergent Space-Time, Black Holes and Quantum Information with Eric Bergshoeff as PI. This positive outcome is especially important for the eEDM programme, because it guarantees a financially sound basis of this experimental programme for the next years. Besides these two new programmes, the VSI also participates in two running *FOM vrije programma's*: Higgs as Probe and Portal and Observing the Big Bang: the Quantum Universe and its Imprint on the Sky. Lastly, the VSI will continue to contribute to the LHCb programme.

This present state of affairs shows that the VSI is in an excellent position to make 2017 into another successful year. With this in mind it's staff members look forward to a fruitful collaboration within the Nikhef partnership!

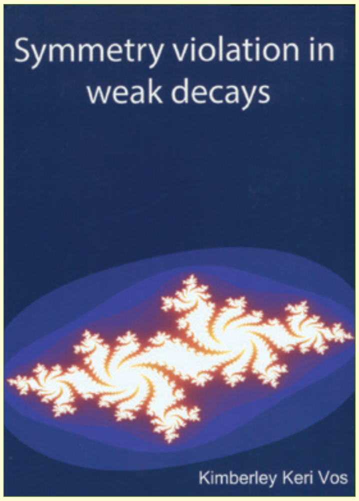
It's wonderful that through the National Nikhef partnership scientists of the Van Swinderen Institute will join forces with other colleagues in the field to reinforce and complement each other's scientific efforts."

— Jasper Knoester (dean University of Groningen)

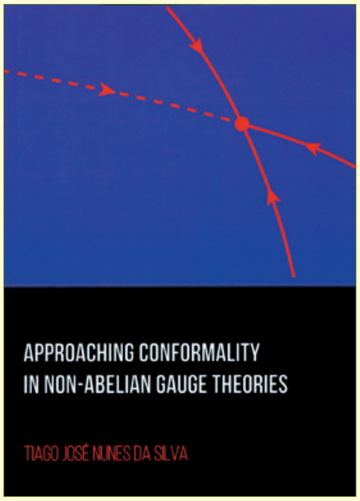
PhD theses in 2016 on research at VSI



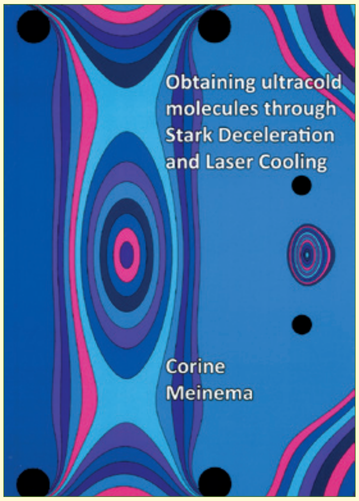
Thomas Zojer
4 January 2016



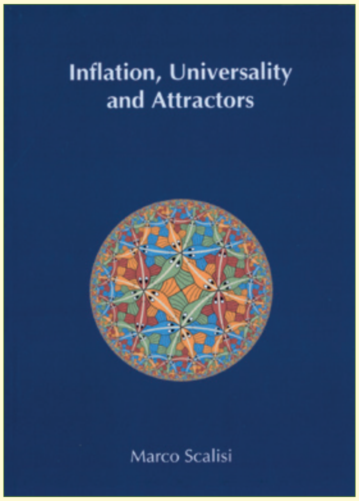
Kimberley Keri Vos
5 February 2016



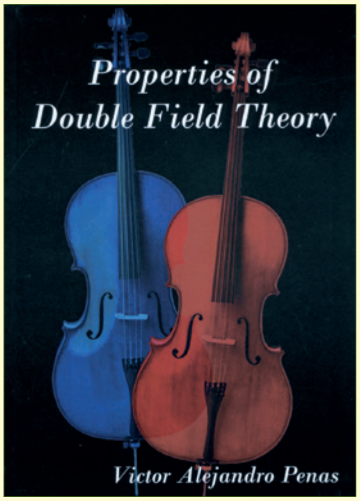
Tiago José Nunes da Silva
22 February 2016



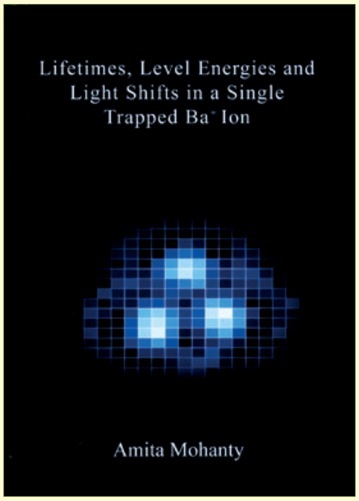
Corine Meinema
13 May 2016



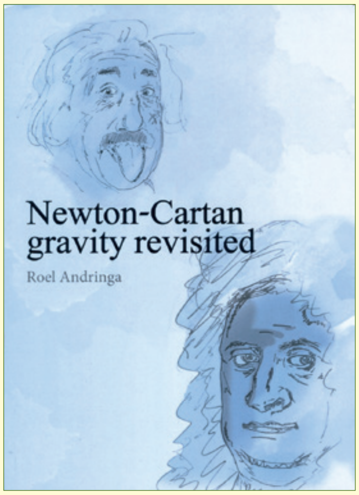
Marco Scalisi
13 June 2016



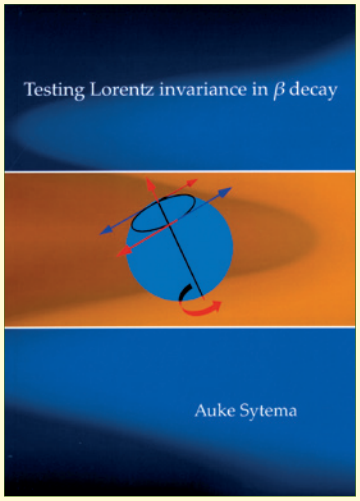
Victor Alejandro Penas
21 June 2016



Amita Mohanty
9 September 2016

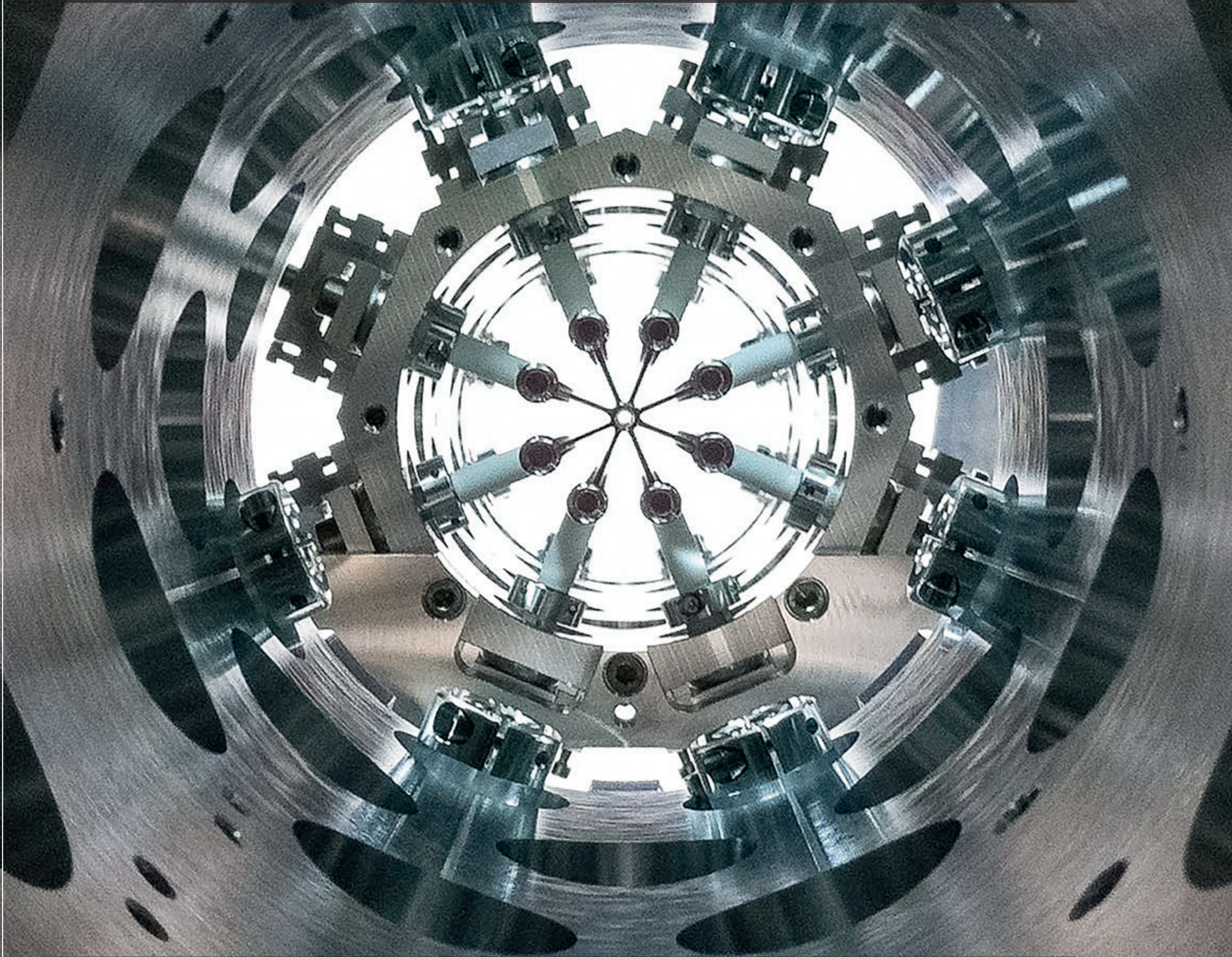


Roel Andringa
23 September 2016



Auke Sytema
5 December 2016

eEDM
Measuring the electric dipole moment of the electron



A view inside the molecule decelerator. A travelling potential is created by a time-varying electric field, applied to over 3000 ring-shaped electrodes that together form a 4 meter long tube. The molecules travel through this tube, and are decelerated in the process. The resulting low velocity allows us to increase the measurement time on the molecules, thereby boosting the sensitivity in the search for the electron's electric dipole moment.

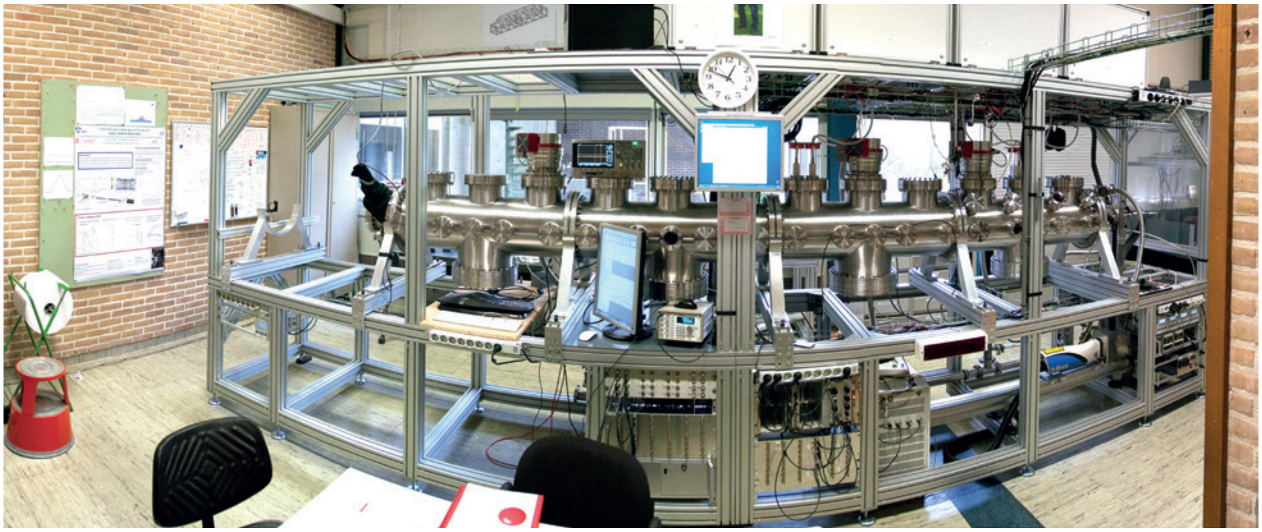


Figure 1. The traveling-wave decelerator in the VSI cold-molecule lab.

Management
prof. dr. S. Hoekstra

Consider the electron. Surely we know all about this fundamental particle? As it turns out, the hunt for the measurement of a basic property – that it so far doesn't seem to have – is motivating a new type of particle physics experiment at a number of research labs worldwide. This elusive property is the electric dipole moment (EDM), which reflects an uneven distribution of the charge. All measurements so far have indicated that if the electron has an EDM (from here on called eEDM), it is smaller than can be measured. This is at first sight not surprising, because the Standard Model of particle physics predicts the electron to be essentially perfectly 'round', and the resulting eEDM is about 10 orders of magnitude smaller than the current measurement sensitivity. So why bother trying to measure this property? It turns out that theoretical models that extend (and thereby try to fix the shortcomings of) the Standard Model all predict an eEDM that is much larger than the Standard Model value! The current best measurement of the eEDM has already put a number of such models under pressure. We have started a new research programmein 2016 to measure the eEDM with unprecedented sensitivity.

Table-top precision experiment

So how to measure the dipole moment of the electron? In the last decade, it has become clear that the most sensitive method is to do the measurement not on a 'bare' electron, but on an electron that is inside a hetero-nuclear diatomic molecule. If such a molecule is placed in an strong electric field, the molecule is polarised. As result, the electron is exposed to a strongly amplified electric field, and this field can be exploited to probe the structure – and thus the EDM – of the electron. The molecule thus effectively amplifies the signal from the EDM. The aim of our experiment is to manipulate, control and probe these molecules in such a way that we can extract the EDM of the electron with optimal sensitivity. This requires extreme measurement precision, since the effects will be small. In contrast to large high-energy collider experiments, in our approach we slow down and cool the molecules in a table-top experiment.

Cold molecules and lasers

We have designed a low-energy precision experiment, based on a pulsed beam of neutral BaF molecules that is being cooled and decelerated using a combination of recently-developed techniques. These techniques are cryogenic buffer-gas cooling, traveling-wave Stark deceleration, and molecular laser cooling. The eEDM is read out using optical, microwave and RF fields in a Ramsey-type spin-interferometer in a carefully shielded and controlled interaction zone. Since we are just starting this research program, a large part of the experiment will be designed, constructed and taken into operation in the coming years. This new Nikhef research programma is carried out in a collaboration of the Van Swinderen Institute (VSI) in Groningen, where the experiment is located, and the VU Amsterdam. One central part however, the traveling-wave decelerator, has already been constructed and is operating routinely in the cold-molecule labs at the VSI in Groningen. Also a large part of the laser infrastructure that is needed to cool, control and readout the molecules is already available, based on a range of low-energy precision experiments that have been operated at the VSI.

An exciting outlook

In the coming year a number of new PhD students will join the current students and staff in our common task to design, simulate and construct the eEDM experiment. We look forward to an exciting eEDM search!

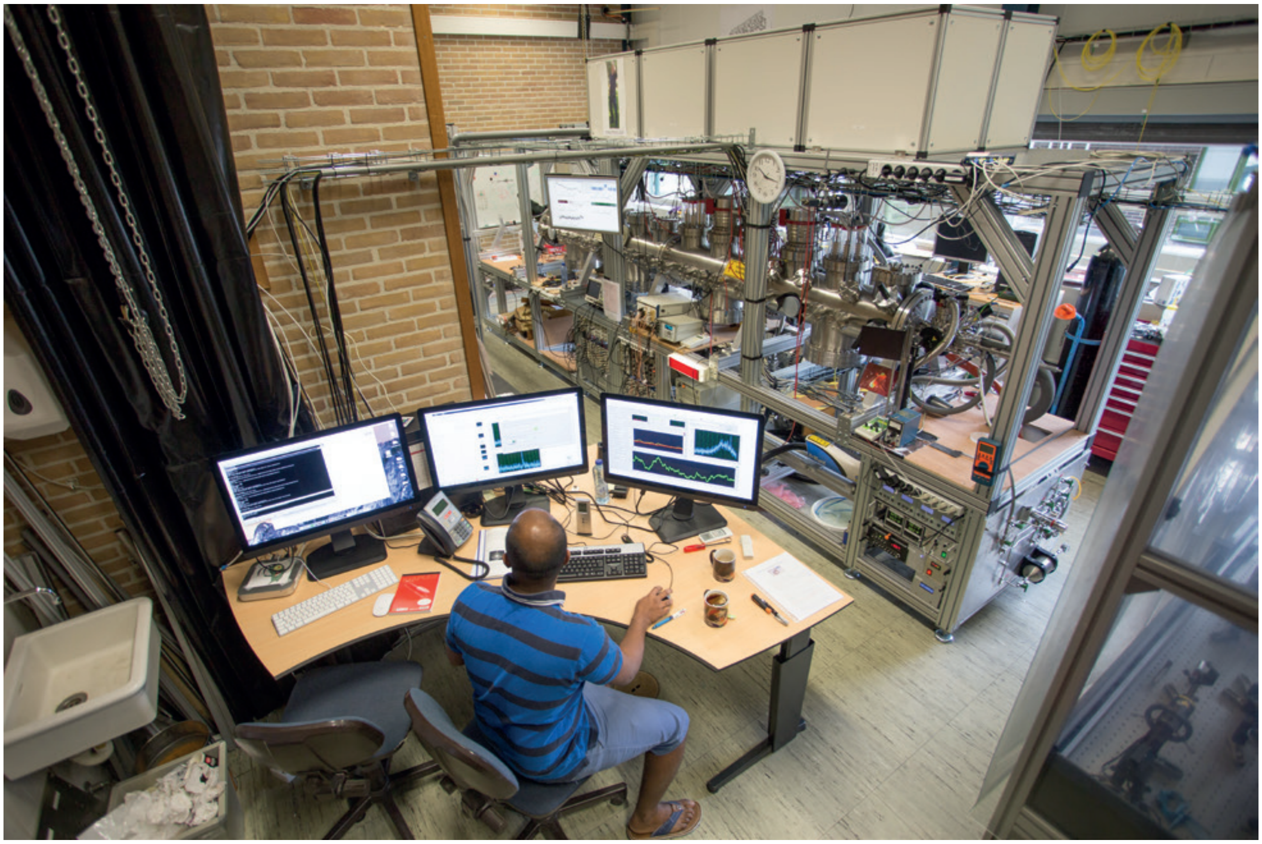


Figure 2. The control room of the traveling-wave decelerator..

Route 5

Building blocks of matter and fundamentals of space and time

In 2016, the almost 12,000 questions posed by the general public 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 Fundamentals of Space and Time'. Route 5 fits the science portfolio of Nikhef very well and is organised by Stan Bentvelsen.

Our understanding of the basic building blocks of matter as well as of the universe as a whole has increased dramatically in recent decades. This has led to the fundamental question whether the evolution and structure of our universe can be understood from the elementary building blocks only. A combination of astronomy, cosmology and particle physics could give a new dimension to this challenging question. What is the impact of the new discovered Higgs particle on the evolution of the universe? How can Dark Matter and Dark Energy be understood in terms of elementary particles? What is the importance of mathematical symmetries?

On 22 March 2016, a dedicated workshop was organised at Felix Meritis, Amsterdam, where researchers from mathematics, high-energy physics, astroparticle physics, astronomy, philosophy, cosmology, quantum-matter, chemistry and theory joined together with people from industry and HBO (Polytechnic) to discuss the theme of Route 5. The goal was to create new and fresh interconnections between the disciplines, and to search for interdisciplinary game changers. With numerous discussions and feedback moments, a wide variety of ideas was collected.

Later, on 29 April 2016, with a dedicated group of people the challenges of Route 5 were formulated in a public document for the *Nationale Wetenschaps Agenda*. The documents of all routes provide the input for a request for a significant increase in funding for science in the Netherlands. The Route 5 document contains three major recommendations and a more general one concerning instrumentation:

Game changer 1: Einstein Telescope

With a yearly extra investment of 8 M€ a leading role can be obtained in experiments that explore the universe with new techniques. On 11 February 2016 the LIGO consortium announced the first discovery of gravitational waves caused by the merger of two heavy black holes. The proposed Einstein Telescope aims at creating a very sensitive successor for the present generation of gravitational wave detectors. A possible location could be in the south of the Netherlands. With a total investment of 300 M€ this could be an opportunity to get a major science facility in the Netherlands.

> *"Particles from the universe have no boundaries, so why should science?"* *

Game changer 2: Dutch Institute for Emergent Phenomena (DIEP)

Emergence connects the smallest with the largest scales in the universe. The collective of building blocks shows often unexpected complex behaviour. Emergence leads to fundamental mathematical and philosophical questions concerning underlying structure and principles. Especially important is whether space-time is an emergent phenomenon. With a proposed annual budget of 10 M€ this new interdisciplinary institute should be studying emergence in many fields of science. A yearly computer investment budget of 5 M€ , shared with other routes, is needed for providing the necessary infrastructure.

> *"True knowledge emerges from testing dreams and visions by concrete experiments"* *

* Quote produced at NWA workshop

Game changer 3: Diversity of Science students

Not all children take their chances in choosing their curriculum. Girls, underprivileged children and children of foreign origin are under-represented among science students. Developing special programmes for school children could help. Moreover professional science communication dealing with questions and issues of ordinary people could help to bridge the gap between scientists and laypersons. With a yearly investment of 3 M€ we hope to achieve a lasting change of society.

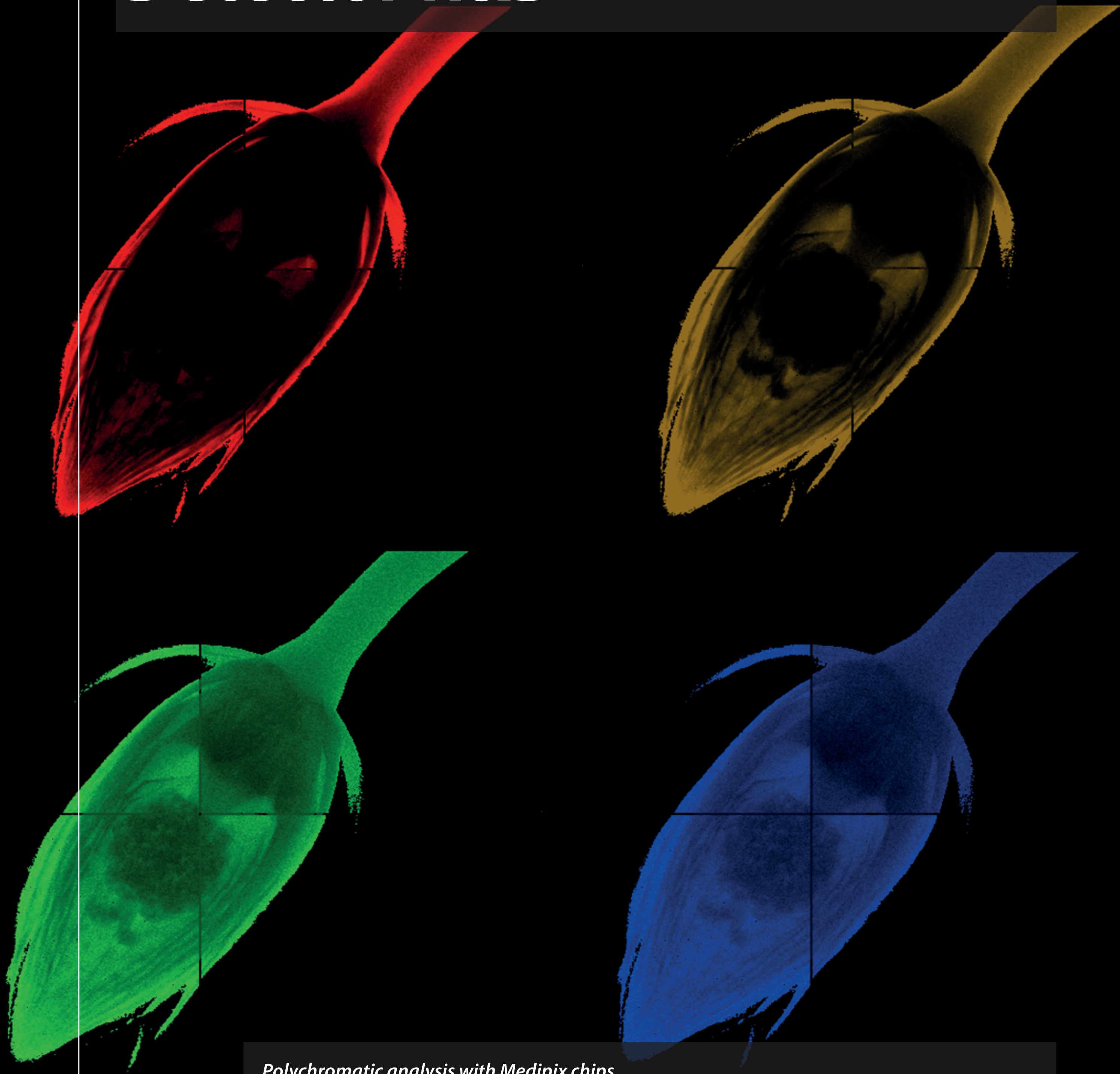
Instrumentation

"Instrumentation can build bridges" *

Accurate observations form the basis of our knowledge about the structure of space-time and the building blocks of matter. The Netherlands has a great expertise and tradition in this area. The NWO institutes play here an important role. By forming centres of expertise for *e.g.* low-noise sensors, sensor networking, technology at extreme conditions etc. both pure science as well as applied science could profit. This requires investments in the infrastructure of 3 M€/year.

"Sharing computational concepts, tools and algorithms in this heyday of massive computing and having an excellent infrastructure are key elements" *

Detector R&D



Polychromatic analysis with Medipix chips.
By using polychromatic x-rays it becomes visible how Rontgen absorption is strongly energy-dependent. Shown here are Rontgen photo's of a flower bud of about 2 cm with photon energies of 7 keV till 25 keV. Red corresponds here to 7 keV and blue to 25 keV. The detector is made of 4 Timepix chips with a 0.3 mm silicon sensor, read-out by a Nikhef ReLaXd system. Timepix chips are developed by the Medipix collaboration of which Nikhef is a member. Special of this setup is the combination of excellent spatial and spectral resolution,

Figure 1. Project leader Martin van Beuzekom together with electronics engineers Bas van der Heijden and Guido Visser, and chip designer Vladimir Gromov (shown right to left) next to the Velopix test stand at Nikhef.

Management
dr. N. van Bakel

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 experiments. Two examples are presented here. In addition, today's push for knowledge transfer to industry leads to international cross-disciplinairy collaborations. Nikhef's role in such scientific instrumentation consortia is highlighted at the end of this section.

Particle tracking with forty million 'smart' images per second

The LHCb collaboration decided already in 2013 to replace the current silicon microstrip detectors in the Vertex Locator (VELO) detector,with a new pixel detector in 2019. The VELO looks closely at the collision region to reconstruct the particle interaction vertices with micrometer precision. After the upgrade, LHCb should be able to read out all collision events at the full rate of 40 MHz, an order of magnitude more data than was foreseen with the current set-up.

The new VELO detector will operate only a few millimetres from the LHC beams, exposing the pixel detector to a high flux of particles. Hence, the VELO will accommodate forty million pixels, each measuring 55 square micrometer, and requires new readout electronics that can handle data rates around 2.5 Tbits/s. To develop state-of-the-art pixel electronics, the DR&D group is closely involved in the Medipix/Timepix collaboration since 1998. The VeloPix chip has been developed for LHCb's new pixel detector and is derived from the Timepix3 chip, however the VeloPix is further optimised for speed and radiation hardness. The chip readout is data driven and zero suppressed: meaning that only pixels with data are readout without instruction from a central control unit. In order to meet the huge data output rate requirement while keeping the power consumption within the budget a dedicated 5.12 Gbit/s output serialiser, the GWT (Gigabit Wireline Transmitter), has been developed.

Each Velopix chip reads out an array of 256 by 256 pixels, is designed in a 130 nm CMOS technology, and a total of 624 chips are needed for the full VELO readout. In order to ensure cooling of the chips within the LHC secondary vacuum the power consumption is limited to less than 3 Watts per chip.

The ASIC was submitted in May 2016 and the first wafers were delivered in September 2016. Excellent results have so far been obtained from the validation testing. Measurements of the noise and threshold uniformity conform to expectations from simulation and promise low threshold operation (below 1,000 electrons). Also the power consumption is about a factor two lower than accounted for. A first assembly with a VeloPix bump bonded to a 200 micrometer thick Silicon sensor has been successfully tested with a charged particle beam at the SPS at CERN, using our SPIDR readout system. The radiation qualification of the Velopix chip is ongoing.

A new vacuum electron multiplier

By placing, in vacuum, a stack of transmission dynodes (tynodes) on top of a CMOS pixel chip, a single free electron detector could be made with outstanding performance in terms of spatial and time resolution. The essential enabling element is the tynode: an ultra (5 nm) thin membrane, which emits, at the impact of an energetic electron on one side, a multiple of electrons at the other side. This defines the Transmission Secondary Electron Yield (TSEY). By means of Micro Electro Mechanical System (MEMS) technology, tynodes and test samples have been realised. The electron yields of tynodes 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 .

With a stack of tynodes mentioned above, a practical vacuum electron multiplier could be made: placed on top of a pixel chip, a new generic digital With a stack of tynodes mentioned above, a practical vacuum electron single electron detector is within reach. By capping the system with a traditional photocathode, a highly sensitive single soft photoncounter (Timed Photon Counter TiPC 'Tipsy') can be realised. The time resolution of this device can be in the order of a few ps since the electron crossing paths between two tynodesis straight, uniform and two orders of magnitude smaller than in photomultipliers

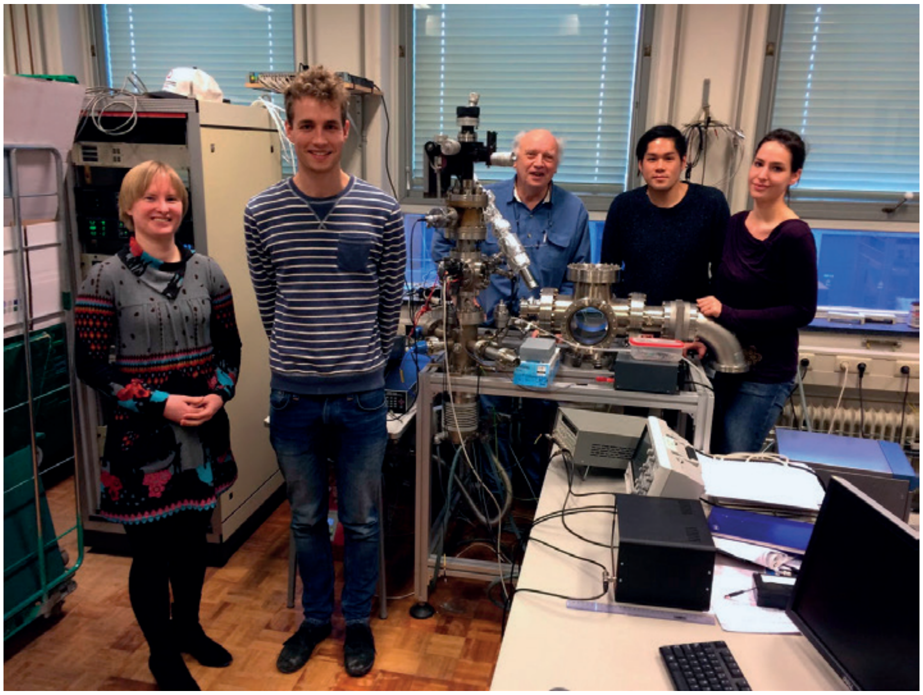


Figure 2. The MEMBrane Group (left to right): Annemarie Theulings (PhD), Wouter de Landgraaf (master student), Harry van der Graaf, Hong-Wah Chan (PhD), Violeta Prodanovic (PhD) around the DyTest: a vacuum chamber with electron gun and four bare TimePix chips, used to measure the Transmission Secondary Electron Yield (TSEY).

Figure 3. Participants of the Annual ENLIGHT Meeting and Training Event, held in Utrecht

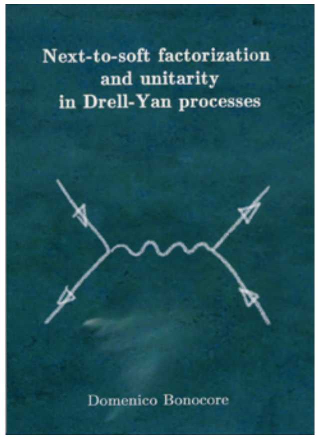
With a TSEY of 5.5, a stack of 5 tynodes results in charge pulses of 5,000 electrons, enough to drive the pixel circuitry of the Timepix3 chip. By manually stacking these tynodes onto the pixel chip, a hybrid Tipsy prototype can be made. A stack of 6 of these tynodes would create 27,000 electrons, enough to drive the circuitry of an all-digital CMOS pixel chip, omitting an amplifier per pixel. After that, MEMS wafer post-processing could be developed to create monolithic detectors. In parallel, the search for higher TSEY at lower primary energy should continue, reducing the required number of tynodes.

Highlights

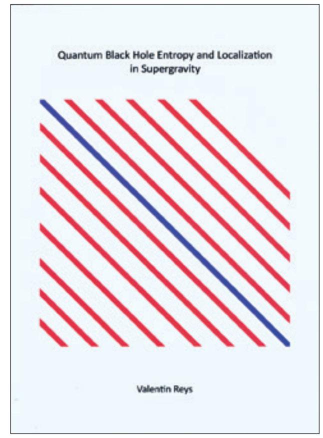
- In June 2016 we have pitched three "Trends, Wishes and Dreams" at the ATTRACT Symposium on Detection and Imaging Technologies. ATTRACT is a new pan-EU initiative to accelerate the development of these technologies for market – through a process of co-innovation with other labs, SMEs, industry and universities. The pitch on *Smart pixels* foresees a large impact on single photon counting and spectral X-ray imaging for medical and industrial tomography systems. The second pitch on *A pixelised detector for thermal neutrons* describes a new generation of neutron detectors with ground-breaking properties. Specifically we expect to realise new generation of detectors by combining CMOS pixel chips with MEMS-built structures, and push for a time resolution down to the picosecond regime. With *The sixth sense: a new detector to observe the universe* we propose detector systems based on novel opto-electronics, (MEMS) accelerometers, and sensitive readout electronics to reduce limiting noise sources in laser interferometry, especially at low frequencies.
- In September 2016 we organised the ENLIGHT Annual Meeting and Training Event. The ENLIGHT network coordinates European efforts in hadron therapy, so that traditionally separate communities like clinicians, physicists, biologists and engineers with experience and interest in particle therapy are working together. Hadrontherapy allows a precise definition of the specific region to be irradiated. This means a tumour can be irradiated with protons while the damage to healthy tissues is less than with X-rays but this requires accurate imaging of the patient. Nikhef works on several techniques to improve medical imaging for hadron therapy.
- Testbeam experience of PhD student Stergios Tsigaridas: *"Detectors often have to cope with a harsh radiation environment and the liberated electrical charge could develop into a discharge which might damage the detector electronics. The purpose of our testbeam experiment was to operate the detector in extreme conditions and test a so-called protection layer. The feeling during the testbeam period is unique. Cern is an amazing place where you have the possibility to meet with experts around the world, socialise and work in a multicultural environment. Definitely preparing and conducting a testbeam is one of the most exciting moments during my PhD."*

PhD student Valentin Reys at the blackboard.

Theoretical physics



Domenico Bonocore
18 May 2016



Valentin Reys
13 June 2016

Management
prof.dr. E. Laenen

Theoretical physics at Nikhef addresses a wide range of research, in part relevant for the experimental program, and some going beyond that. The highlights mentioned below exemplify both these aspects. To do this research, group members work with each other as well as with colleagues from all over the world, a flexibility of working that leads to lively exchanges, and rapid spreading of new ideas.

On the quite theoretical front, Nikhef theorists managed to construct all N=4 conformal supergravity theories (that is, gravity theories extended such that they are invariant under four types of super symmetry, and have conformal symmetry as well), a result that has long been looked for.

In the physics of B_s-mesons, a new strategy was devised to explore CP violation through its decay to charged kaons. Moreover, its oscillation into its antiparticle and back can also be used as a tool for such exploration when charm quarks are involved.

A substantial amount of new insight was gained in the structure and perturbative behaviour of QCD. New classes and types of large logarithmic corrections were resummed to all perturbative orders, or shown to have predictable patterns. The role of initial state gluons and their transverse momenta in probability functions for incoming protons was clarified in various settings, such as polarised high-energy scattering.

Group members continue to explore the notion that the Higgs boson and the cosmological inflaton are one and the same particle. This year the ultraviolet sensitivity of this notion was studied, and it was found that the parameters of the Cosmic Microwave Background spectrum are poorly related to the top quark and Higgs mass measurements at the LHC.

Besides scientific papers researchers in the group publish computer codes that can be used by others for a variety of purposes. This year saw the release of Axodraw v2 (for very nice renditions of Feynman diagrams), NNLLFast (for precise estimates of squark and gluino production rates), and of FORCER (a FORM program for four-loop propagator diagrams, which even contains automatic code generation).

FOM-projectruimte Robert Fleischer & Marcel Merk

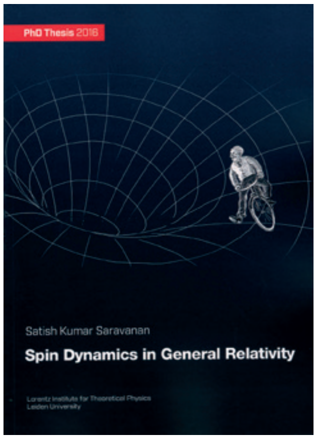
A FOM-*'projectruimte'* was granted to Robert Fleischer of the Nikhef theory group and Marcel Merk of the Nikhef LHCb group for their (combined theoretical and experimental) proposal "Very rare beauty decays: a magnifying glass for quantum physics".

"Through research into very rare forms of particle decay, the first evidence for which has been found in data from the Large Hadron Collider, the researchers hope to discover new physics that possibly reaches beyond the Standard Model of particle physics. 'The awarded project consists of a combination of a new theoretical (Robert Fleischer) approach and an experimental (Marcel Merk) one to focus on these extraordinary quantum processes."

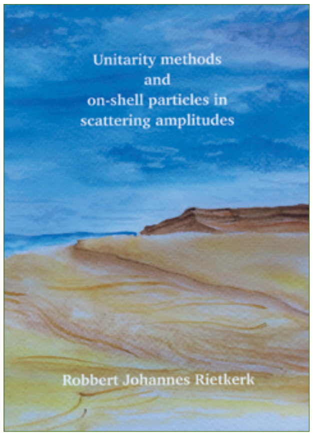
Amsterdam Master of Physics and Astronomy Award 2016 Ruben Jaarsma

Ruben Jaarsma (middle) at the award ceremony among his fellow competitors.

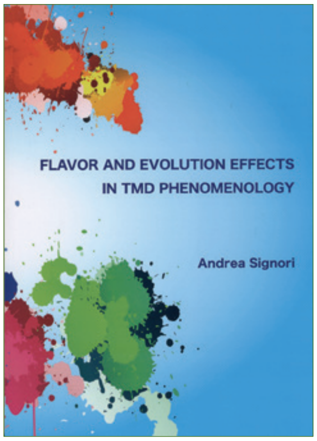
Ruben Jaarsma won the Amsterdam Master of Physics and Astronomy Award 2016 for the best presentation of a master research project with his talk "Hunting New Physics at the LHC High-Precision Frontier". Students of the joined master programmes Physics and Astronomy of the University of Amsterdam and the VU University Amsterdam were competing for this award at the Amsterdam Master of Physics and Astronomy Symposium 2016. Jaarsma conducts his research on B physics in the Nikhef Theory group.



Satish Kumar Saravanan
7 July 2016



Andrea Signori
17 October 2016



Robbert Johannes Rietkerk
19 October 2016

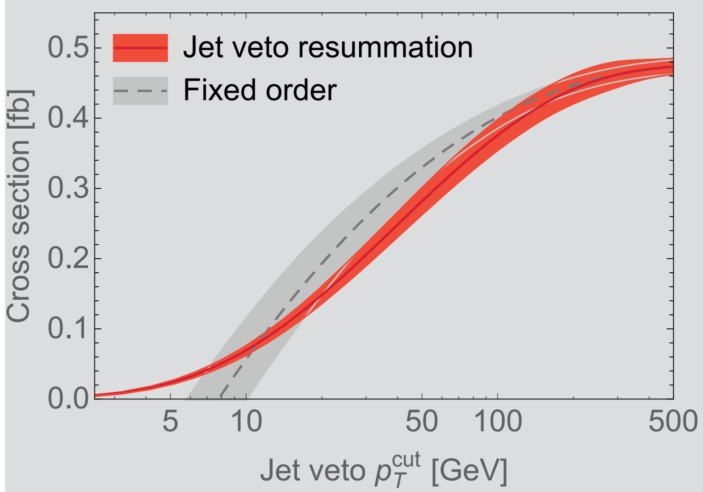
Jet vetoes in new physics searches at the LHC

F.J. Tackmann, W.J. Waalewijn and L. Zeune,
Impact of Jet Veto Resummation on Slepton Searches
JHEP **1607** (2016) 119, arXiv:1603.03052 [hep-ph]

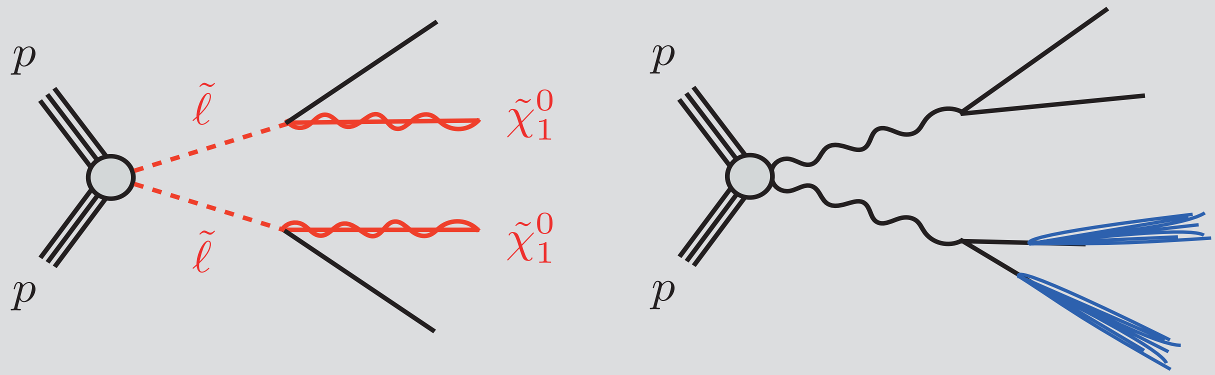
The LHC experiments undertake enormous efforts to search for particles predicted by new physics models, trying to find answers to the big, open questions of modern physics, such as 'What is dark matter?'. To distinguish the new physics from the overwhelming Standard Model background, experimental analyses require a specific number of jets and demand the absence of ('veto') additional jet activity. Already an important experimental tool in new physics analyses, the importance of jet vetoes will further increase when a new particle is discovered, facilitating clean and precise measurements.

However, jet vetoes lead to additional complications in the theoretical description of the new physics events. They introduce large logarithms which require resummation, a method to sum an infinite number of logarithmic terms in the theoretical prediction.

Members of the Nikhef theory group were the first ones to analytically calculate a new physics process including jet veto resummation. Taking the production of supersymmetric leptons as example, they found that the jet veto effect and in particular the associated theoretical uncertainties are large, which has a sizeable impact on the present and future LHC limits on the mass of these new particles.

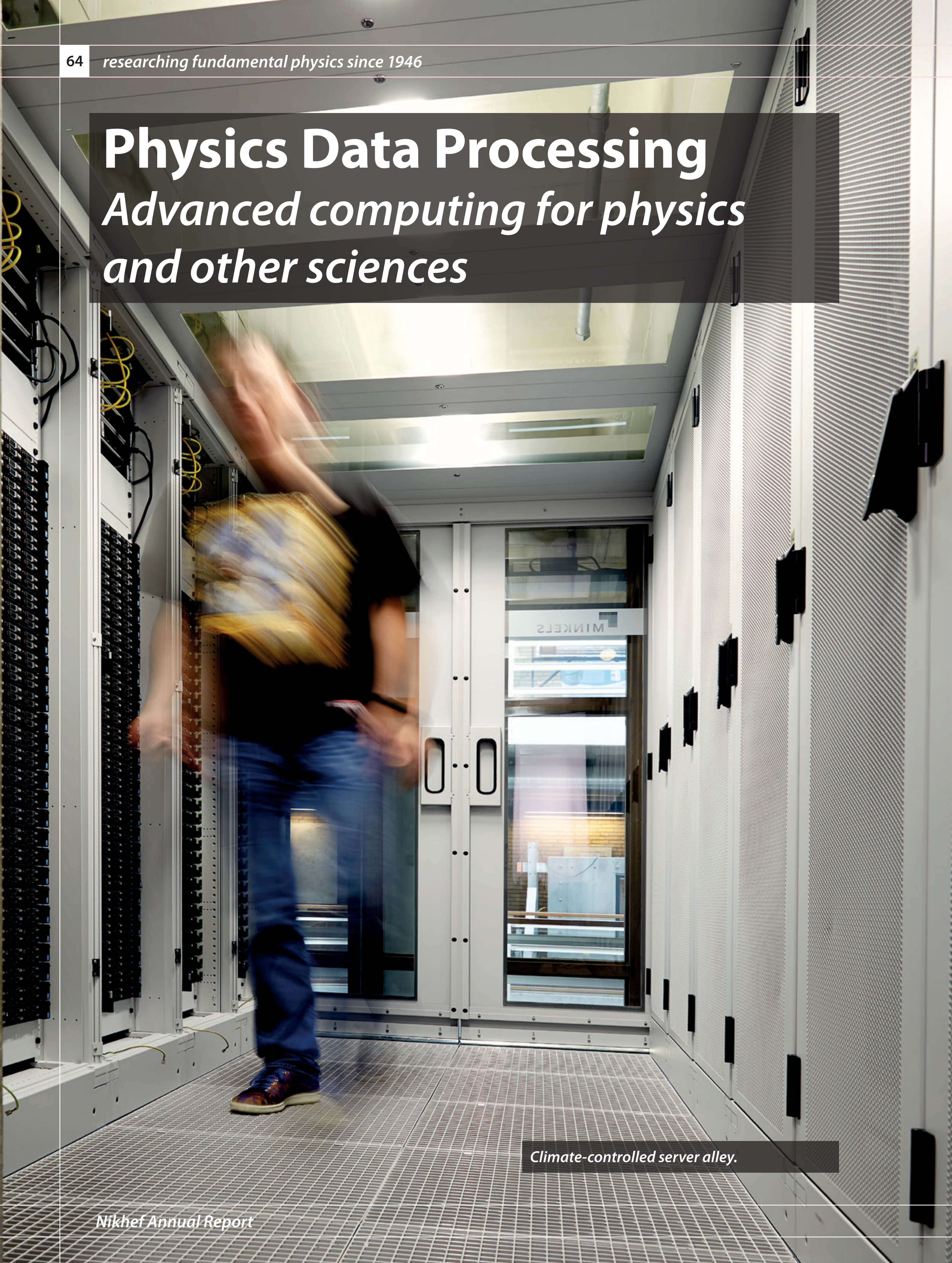


The improvement of resummation on the cross section as opposed to the fixed order compution: notice how much narrower the uncertainty bands are.



The production of supersymmetric leptons on the left, and a background process with jets on the right.

Physics Data Processing
Advanced computing for physics and other sciences



Climate-controlled server alley.

Daniela Remenska
8 February 2016

Management
dr. J. Templon

The Dutch Tier-1 for LHC Computing, roughly half of which is housed in the Nikhef Data Centre, ran well during 2016, providing about 50% more CPU cycles than promised to our LHC experiments. The extra cycles came from unused allocations to other groups on the National e-Infrastructure.

New Developments

Our cloud infrastructure plans reached the advanced prototype stage in 2016. The developments are made in close collaboration with SURFsara and the University of Groningen, following also developments by our international colleagues. We expect the facility to be operational in the first half of 2017.

Part of our 'cloudification' project includes software-defined networking which will provide both the necessary isolation (security) as well as connectivity (bandwidth); in Q3 2016 we took delivery of an advanced switch '*kroonsteentje*' with an internal bandwidth of approximately 100 Tbit/s and capable of the required programmability. Not only does this switch enable our cloudification, it also lays a foundation necessary for the data rates expected in the HL-LHC era.

Cloudification of the facility provides several advantages in flexibility of resource provisioning. Perhaps the most important is that, outside of high-energy physics, very few scientists are interested in the grid computing paradigm. As long as LHC-scale data sets are not involved, there are alternatives to grid that are much more user-friendly. 'Cloud' is one of them, and others can easily be instantiated as a platform running on top of a virtualisation cluster. Whereas in 2013, 13% of our computing cycles were provided to researchers outside of high-energy physics, in 2016 this figure was just 4%, the other groups having moved on to cloud infrastructures available elsewhere. Serving our mission as a node in the Dutch National e-Infrastructure requires our move to a more flexible base system; the current LHC Computing Grid node will run transparently as a virtual grid site on top of the cloud platform.

Nikhef's security officer Sven Gabriel teaches a class on data security.

The group took delivery of one of the first Knight's Landing (Intel) Development systems, and performance studies are being made of several applications. The PDP group was also involved in the design and specification of a special machine for the theory group, designed for execution of large-scale FORM calculations. The machine includes 768 GB of RAM and about 20 TB of fast solid-state disk drives acting as extended memory for FORM.

Gravitational Wave Searches

Starting in late September 2016, the VIRGO and LIGO collaborations began to make use of our grid cluster. For Europe, Nikhef is currently second only to CNAF in amount of computing cycles (about 400 cores, averaged the last two months) provided. Currently most of the cycles go to searches over data looking for sources of continuous emission of gravitational waves; developments are ongoing to extend this to other classes of gravitational-wave searches.

Securing federated communities

The gravitational wave community is also at the forefront of federated authentication and collaboration technology, and one of the most active groups in Authentication and Authorisation for Research and Collaboration. In this global effort, Nikhef contributes both technology and services that bridge 'web based' single sign-on authentication systems to data-intensive computing infrastructures such as EGI. This year was especially successful: our 'RCauth.eu' service was successfully piloted by both EGI and ELIXIR (the ESFRI life sciences information infrastructure), and was subsequently selected as a core activity for the future of EGI. Our accreditation of this service to the Interoperable Global Trust Federation IGTF also represents the success of policy coordination, where we working closely with the global research and education community to improve trusted identity and the response to security incidents.

Operational security is also a key element in the 'cloudification' of both our infrastructure and those around us. Where experience has shown that systems hardening and configuration is not necessarily a forte of researchers, our own network and systems design will be based around the operational security experience we gained by coordinating the European EGI security response team.

Ensuring Grid security: an ethical hacker's dream

Sven Gabriel
Computer Technology

By Laetis Kuipers

As the Security Officer for Nikhef and EGI, the organisation coordinating the European Grid Infrastructure, Sven is responsible for securing, protecting and improving an immense computer network so that its multi-disciplinary user communities may carry out their work safely and without interruption. "To safeguard the Grid's integrity," he explains, "our incident response team launches controlled attacks on designated parts of the framework to monitor the system's response and subsequently to make sure that the issue will not arise again. You could say that my job is what many ethical hackers dream of."

"Our security teams and our technicians are very much aware that a secure computer environment is absolutely crucial to the continued success of Nikhef's research projects, and our users realise this too. Together, we have built a nicely balanced, symbiotic relationship. Driven by the demands of fundamental research, we have gathered new diagnostic security knowledge through which we can offer our global users – and this concerns as many as 350 research institutes worldwide – a series of innovative tools in return. We are always very open in our communications, which means that people always know what we are up to. They realise that any temporary nuisance they may experience as a result of our work will prevent bigger and more dangerous events from developing. I think this also typifies the relevance of our work."

With a background in computational chemistry, meteorological sciences and grid administration, Sven has extensive experience with many different simulation techniques. With his passion for computations and solving puzzles, he sees his current position as one of the best in the world. "Nothing beats a good challenge," he says, "and I very much like dealing with things that are complex: it's in my nature. And here at Nikhef I have the chance to do this not only on the relatively modest scale of our own institute, but also on a larger European and global scale. Moreover, I can share our knowledge and solutions: internally with the community of fellow security officers, a close-knit and open-minded group of experts, and externally with the larger community of users. This is done through community challenges and training programmes, perfect examples of the type of knowledge transfer and valorisation that forms an integral part of Nikhef's mission."

Technical Departments

Electronics Technology

Below a summary of the various projects in the department:

- ATLAS DAQ FELIX; (Front-End Link eXchange(FELIX) system), a common interface system for the ATLAS data acquisition, detector control and timing and control systems. The FELIX team demonstrated the required design progress in Design review in 2016. This was realised first using industrial evaluation boards and later with a prototype board that is based on an advanced Xilinx FPGA. The team now continues with the final design to be delivered in fall 2017.
- KM3Net first deployments and use of the optical network that is designed by the team in the electronics department:
  * Recovery of a detector line and review process of all major subsystems for stability and reliability improvements of the whole system.
  * Improvements in the stability and accuracy for timing synchronization implemented now in firmware and proposed for inclusion in hardware. Also calibration methods are further developed to achieve accurate timing (1 ns) for the foreseen number (~12,000) of optical modules in the final system. The used timing system 'White Rabbit' has spin-off for other experiments (*e.g.* CTA) with whom we already exchange useful experience. For calibration techniques we collaborate with the Free University of Amsterdam.

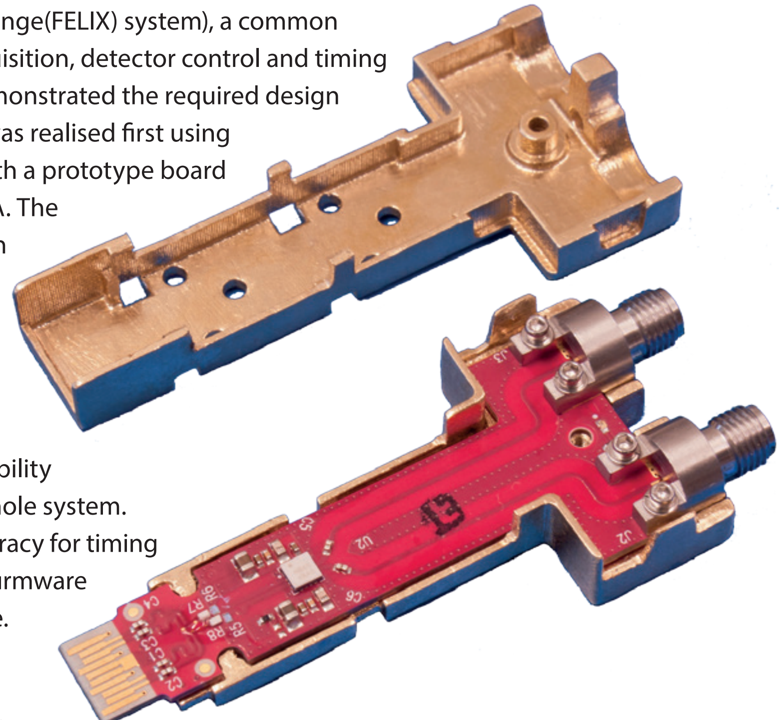


Figure 1. Picosecond Timing Calibration Test Tool; enclosure developed with 3D-design tools in co-operation with the Mechanical Technology department.

- LHCb SciFi readout system and board design with a special feature: "Design for manufacturability". This methodology is required for high-quality boards to be produced by selected industrial manufacturers. The final production may require a European tender procedure, and the present design method will result in the correct specification and quality criteria. This methodology was presented at the TWEPP2016 workshop in Karlsruhe by Wilco Vink.
- IC design: the electronics department contributes to the CERN RD53 R&D project. The project's purpose is to develop a common platform for ATLAS & CMS that can be used as a basis for a final pixel front-end chip for ATLAS and CMS with very high radiation tolerance.

Moreover, the ET delivered the following IC design results in 2016:

- Collaborative design of the ATLAS RD53 DRAD test chip for Radiation-tolerant digital library characterization. The chip is produced and characterised before and after irradiation and delivered very useful results in preparation for the RD53 pixel chip.
- Nikhef prototype: GWT65: a test chip for our 5 Gbps serialiser design in 65 nm CMOS technology. The circuit can be validated before integration in the RD53A chip, to be produced around summer 2017. The RD53A is the first common pixel front-end chip for ATLAS & CMS.

Figure 2. ATLAS FELIX design and integration workshop at Nikhef in October 2016.

- Contribution to LHCb VeloPix (LHCb Velo front-end pixel chip); produced in 2016 and tests are still on going. This chip is presently the most advanced pixel readout chip in the sub-atomic physics community; the IC contains about 190 million transistors.
- For testing the VeloPix IC, an available readout system for MediPix & TimePix IC's (SPIDR) was used and modified. Required was a chip readout speed of 20 Gbps (!) over 4 serial data lines. This is implemented and was made available in time.

New Techniques

This year Nikhef invested in an (expensive) advanced, high bandwidth (33 GHz) Real-Time oscilloscope for the Electronics department to characterise and debug serial data communication with FPGA's and ASIC's (like VeloPix).

Concerning personnel developments, the introduction of a flexible layer of personnel at Nikhef forces the department to actively choose what belongs to the core business and what not. The realisation of projects by outside companies is then an ongoing challenge. A successful example is the development of a frame grabber by TOPIC Embedded Systems for the ATLAS detector alignment. The system is installed in 2016 at CERN.

Computer Technology

For the Computer Technology Department, 2016 was a year of structural improvements and updates to prepare our systems for the future. For the system administration activities, this is a normal way of working to ensure smooth operation of the infrastructure, which from the point of view of its users takes place largely behind the scenes. This year's main efforts from the Experiment Support group and the group supporting the local analysis facility are also focused on preparations for the future.

Experiment Support

The barrel alignment system of the ATLAS muon spectrometer consists of more than 5,800 optical channels, each of which comprises a camera, a light source, a coded mask and a lens. The channels are eventually connected to an array of eight computers with frame grabbers. These computers with frame grabbers have been running for more than 10 years and needed to be replaced. Not only were they running an old and no longer supported operating system, but also the chances that hardware failures would disrupt operation of the alignment system have become too large to be acceptable. Replacement of the computers and their operating system triggered two major problems: there is no driver software for the frame grabber cards anymore that works with more recent operating systems, and newer computers no longer support the hardware interface used by the frame grabber cards. Consequently, alternative frame grabber cards were needed. Unfortunately, the market does not offer off-the-shelf alternative frame grabber cards that would be compatible with the 5,800 cameras and replacing the cameras was not an option. In close collaboration with the Electronics Technology Department, the search for an alternative solution resulted in a connection with the Dutch company TOPIC in Best, which is specialised in development of embedded software systems. TOPIC could build an embedded solution based on FPGA technology with an ARM processor, which is essentially a standalone small Linux server that can be configured and connected via the network. The new systems could be configured such that they are fully compatible drop-in replacements for the outdated computers and frame grabber cards. At the end of 2016, after shutdown of the LHC, the new solution has been installed in the ATLAS experiment. In 2017 a similar upgrade of an equivalent system in the LHCb experiment is foreseen.

Local Analysis Facility

The local analysis facility consists of a compute cluster *'Stoomboot'* with about 800 cores of processing power and a dedicated, high-performant storage system, which provides about 200 Terabytes disk capacity for storage of large data sets. This facility is known to give Nikhef's physicists a competitive advantage over research groups in other institutes.

After almost five years, both the hardware and software for the old storage system needed an update to increase its capacity to accommodate larger data volumes. Renewing the hardware is rather straightforward with plenty of choice by various vendors, but there is only a limited choice for a suitable storage system. A simple expansion into new hardware using the old system was not feasible due to scalability issues. Instead after careful consideration we opted to investigate the dCache storage system developed at DESY. dCache is widely used in the Grid computing context and has the required stability and scalability absent from the old storage system, but had not been used as storage for a local analysis facility. To ensure dCache would work in the context of our analysis facility we worked closely with the dCache developers to test, debug and deploy dCache for this new use case.

These efforts have resulted in taking the dCache system in production. It currently offers a net capacity of 550 Terabytes and will be enhanced with another 300 Terabytes in early 2017, leading to a fourfold increase of storage capacity. The system also has a better performance under high load conditions and supports multiple protocols for accessing the data, allowing more simultaneous analysis jobs to access the ever-growing data sets.

Mechanical Technology

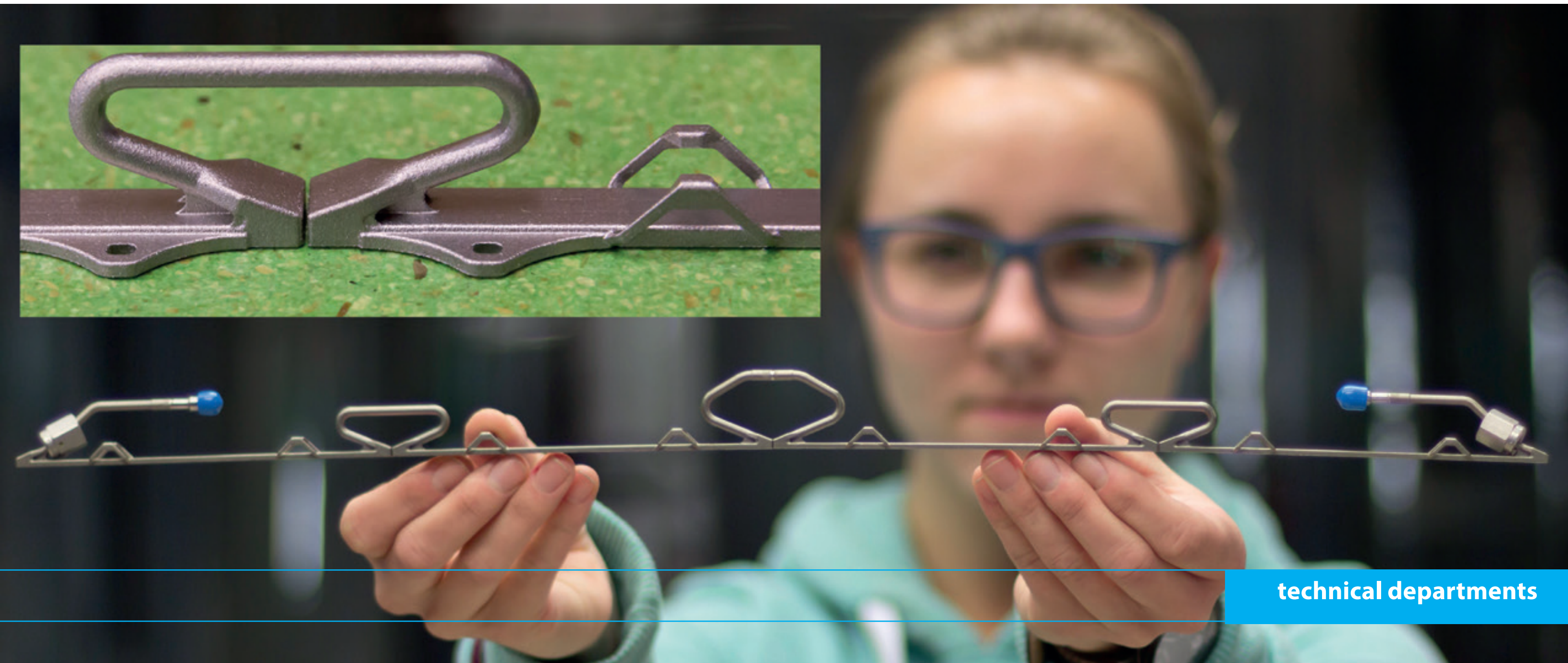
At the Nikhef mechanical technology department, the activities for the upgrades of the LHC detectors Alice, ATLAS and LHCb have come to fruition, and will continue to consume most of the department's resources for the next year. Some highlights of 2016 are:

Figure 3. Eric Hennes won the Best Poster Award 2016 at the Conference on Precision Mechatronics of the Dutch Society for Precision Engineering (DSPE)

- The complex geometry of two monolithic half-size RF box prototypes for the LHCb Vertex Locator (VELO) have been successfully machined, with the critical foil milled to thicknesses of 0.5 and 0.25 mm. Moreover, in December the first full-size box has been almost finished.
- The final design of the readout box of the Scintillating Fiber detectors (SciFi) for LHCb has been tested. It includes a glass-filled nylon thermal insulation structure and 200 micron thick titanium cooling structure, both 3D-printed (see Fig. 4), as well as a high-precision positioning tool to ensure proper alignment of the fiber modules and the Silicon Photomultiplier sensors (SiPM).
- An in-house developed tool for cutting at high precision (20 micron) flexible printed circuits carrying the monolithic active pixel sensors of the Alice Inner Tracker.
- Mechanical highlights for the astroparticle physics projects:
- The mechanical design of the Scintillator Surface Detector (SSD) for the upgrade of the Pierre Auger Observatory has been successfully prototyped.

A total of 80 Digital Optical Modules (DOM) for KM3Net were produced in-house in 2016. The production capacity has grown to 200 DOMs per year.

Figure 4. Lara Veldt shows two connected 3D-printed, 0.2 mm wall thickness multichannel titanium cooling-structures, to be mounted inside the read-out box of the scintillation fiber tracking detector of the LHCb upgrade.



Awards & Grants

Sijbrand de Jong, Raimond Snellings and André Mischke new members Academia Europaea.

Sijbrand de Jong, Raimond Snellings and André Mischke were elected new members of the Academia Europaea. The Academia Europaea (formed in 1988) is the pan-European academy of science, humanities and letters, with a membership of over 3,500 eminent scholars who collectively aim to promote learning, education and research, drawn from all countries of Europe, and all disciplines, nationalities and geographical locations.

Frank Linde new member Royal Netherlands Academy of Arts and Sciences

Frank Linde has been selected as a new member by the *Koninklijke Nederlandse Academie van Wetenschappen* (KNAW, Royal Netherlands Academy of Arts and Sciences).

The Academy has about five hundred members. Academy members are prominent researchers active in all the disciplines, and are appointed for life. As the forum, conscience, and voice of the arts and sciences in the Netherlands, the Academy promotes quality in science and scholarship and strives to ensure that Dutch scholars and scientists contribute to cultural, social and economic progress.

Jos Engelen Officer in the Order of Orange-Nassau

Jos Engelen, former Nikhef director (2001–2003), was awarded the title Officer in the Order of Orange-Nassau. He is honoured for his outstanding achievements in the field of science both in the Netherlands and internationally. As deputy Director-General of CERN (2004-2008), he played an important role during the construction of the Large Hadron Collider, while as chairman of NWO (2009–2016), he contributed greatly to the advancement of science in the Netherlands.

2016 Breakthrough Prize in Fundamental Physics for neutrino oscillation

The 2016 Breakthrough Prize in Fundamental Physics (3 M$) was awarded to five experiments investigating neutrino oscillation, among which the KamLAND experiment in Japan and the Sudbury Neutrino Observatory (SNO) in Canada. Nikhef researchers Patrick Decowski (in the red circle on the KamLAND collaboration photo below) and Christopher Tunnell (SNO) are among the prize-winning members.

The award was presented for the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics.

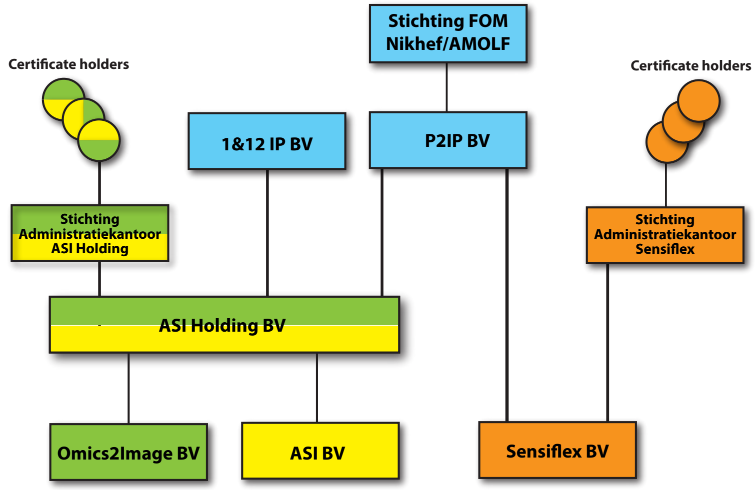
Special Breakthrough Prize for detection of gravitational waves

A Special Breakthrough Prize in Fundamental Physics (3 M$) was awarded in 2016 recognizing scientists and engineers contributing to the momentous detection of gravitational waves. The award will be shared between two groups of laureates: the three founders of the Laser Interferometer Gravitational-Wave Observatory (LIGO), and the 1,012 contributors to the experiment. A total of 22 authors from Nikhef share in the prize. The prize was awarded to the contributors for recording gravitational waves from two black holes colliding over a billion light years away.

The Breakthrough Prizes honour important, primarily recent, achievements in the categories of Fundamental Physics, Life Sciences and Mathematics. The Breakthrough Prize in Fundamental Physics was founded in 2012 by Yuri Milner to recognise those individuals who have made profound contributions to human knowledge. It is open to all physicists – theoretical, mathematical, experimental – working on the deepest mysteries of the Universe.

Knowledge Transfer

Valorisation & Spin-off Activities



The current legal structure of Nikhef's start-ups.

2016 has been another turbulent year for Amsterdam Scientific Instruments (ASI). The focus has continued on expanding sales channels and opportunities beyond the scientific market. ASI has agreements in place with a number of resellers in China, Japan, Russia and India. ASI has also established strong relationships with multinational scientific equipment companies and partners that will integrate ASI's core technology in a total solution for their customers. These relationships demonstrate the added value of ASI in collaborative projects together with academic and industrial partners. The increasing efforts in business development have resulted in a turnover of more than 1 M€ in 2016.

A common research study project with Nikhef and FEI has been carried out in the realm of chip design to investigate opportunities for the further developments of fast timing circuits. For FEI this concerned the field of direct electron detection for transmission electron microscopy. Although the results are interesting no follow-up has yet been agreed.

2016 also saw a restructuring of the shareholder positions and the balance sheet of ASIH (ASI Holding). P2IP bv is now a 'FOM-only' holding, whilst 1&12 Investment Partners has obtained a direct share in ASIH.

Innoseis, Nikhef's gravitational wave detection spin-off, has achieved another series of milestones this year. The focus was on developing market acceptance of Innoseis' ultra-low power seismic sensors, which involved a number of pilot projects around the globe with various parties including Shell at three different locations. This has helped to build strong relationships with many important industrial parties and potential customers. The feedback has been overwhelmingly positive due to the demonstrated improvements in operational efficiency compared with conventional products. It was a great year in terms of publicity too, with articles by, amongst others, Bloomberg and *Het Financiële Dagblad*.

The sensors were also used in tests with security parties such as the Dutch police to demonstrate the feasibility of applications like intruder movement or explosion localization, and at the Advanced Virgo site to determine the seismic motion and subsurface characteristics there. Development on the engineering side has led to new features and integration with the internet-of-things technology. In 2017 Innoseis will look to further strengthen partnerships across the industry and scale production for major sales of its products.

The *CERN-BIC* at Nikhef has received another Expression of Interest early 2016. This 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.

Industrial contacts

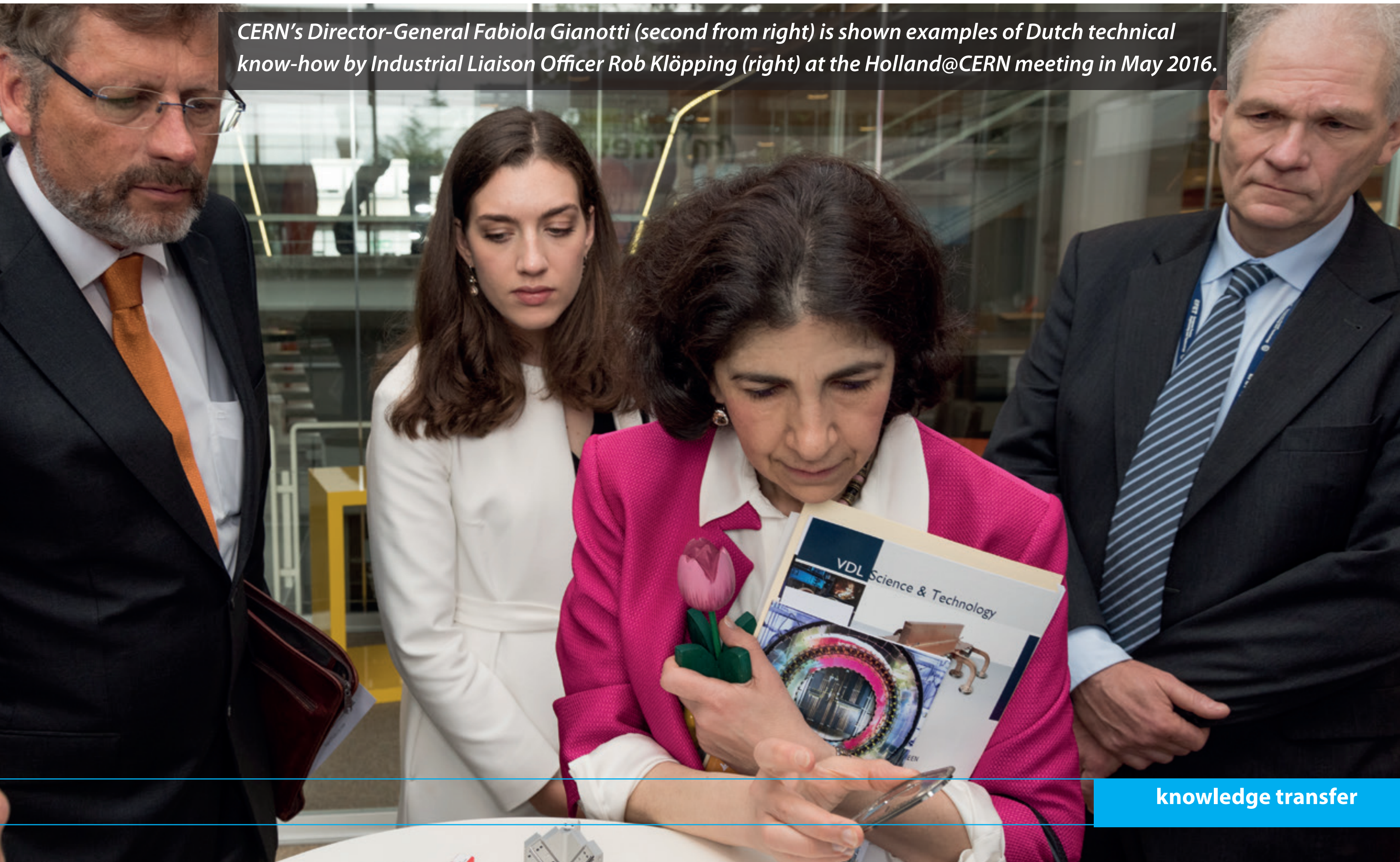
In the area of seismic sensoring Nikhef closed another agreement with Shell for the development of sensors using the wireless communication technology, with Innoseis as subcontractor.

Nikhef has also agreed a follow up project with steel producer Tata Steel, evaluating the viability of muon radiography for the analysis of the homogeneity of large vessels with (liquid) steel.

Nikhef's datacenter activities, including those for customers of the Amsterdam Internet Exchange, *AMS-IX*, and also including Nikhef's role in the Dutch national e-infrastructure for research, have further grown, reaching over 3.3 M€ turnover in 2016. The measures taken to increase the energy efficiency of the Nikhef datacenter, have resulted in a significant decrease in the PUE (Power Usage Efficiency) to a value of 1.27 over the year 2016 as compared to around 1.5 in the years before.

The ENLIGHT Annual Meeting this year was held in Utrecht, on 15 and 16 September. For the first time, ENLIGHT has brought training in the core program of its network meetings, dedicating a full day (17 September) to lectures on key aspects of particle therapy. The meeting was organised by Els Koffeman and Jan Visser from Nikhef and it was attended by almost 100 participants from 15 countries. The annual meeting of the ENLIGHT network gathers experts and delegates from most of the European centers and research institutions working on particle therapy for cancer treatment.

Finally, the network of Industrial Liaison Officers (ILOnet) has again organised several meetings and conferences (see http://www.bigscience.nl/nl/agenda) with the main aim of positioning Dutch industry for acquiring purchase orders in large international research facilities, such as the Holland@CERN meeting in May 2016. More details are available in the Annual Report of the ILOnet.



CERN's Director-General Fabiola Gianotti (second from right) is shown examples of Dutch technical know-how by Industrial Liaison Officer Rob Klöpping (right) at the Holland@CERN meeting in May 2016.

Outreach & Communications

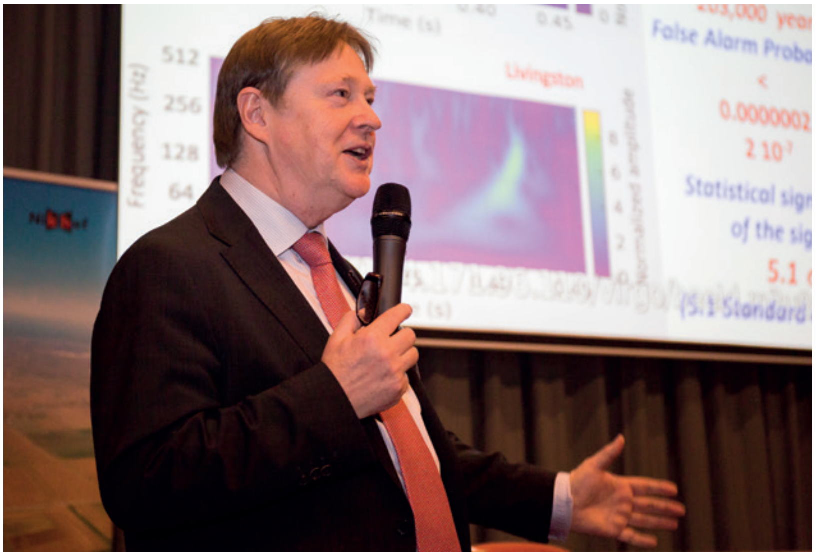
2016 Starring gravitational waves

Hundred years after Einstein had predicted them, on 11 February 2016, scientists from the LIGO-Virgo-collaboration, among whom many Nikhef researchers, announced they had discovered gravitational waves. An announcement which had been preceded by many decades of research, of designing and building detectors, setting up and conducting data analysis, but also by exciting months of rumours flying around and preparations behind closed doors.

It all reached its climax in an unforgettable statement, *"We have detected gravitational waves. We did it"*, followed worldwide by a lot of excitement. The partners in the LIGO-Virgo-collaboration announced this breaking news in simultaneous press conferences in the U.S. and Italy, while for the Dutch media and public Nikhef had organised a press conference in Amsterdam. The press came in droves. From the main Dutch national television news channels, to radio reporters and newspaper journalists, everybody wanted to be a witness to science history being made. The Nikhef researchers who played an important role in this breakthrough discovery hurried from one interview to the next. Basically instantaneously, countless articles were published online. On the evening news, Dutch viewers were told the ins and outs of gravitational waves and why this discovery was so important. And the next morning all national and regional newspapers printed long articles featuring gravitational waves, some even on the front page.

Surely one of the TV highlights was that Nikhef researchers Jo van den Brand, Chris Van Den Broeck and Gijs Nelemans were invited to the most popular Dutch talkshow *'De Wereld Draait Door'*, and could thus share their enthusiasm with more than a million viewers. They and the other Nikhef researchers of the gravitational waves group were also interviewed in, among other programmes, the *'Jeugdjournaal'*, the *'NOS-journaal'*, *'Kennis van NU TV'* and *'RTL4 Nieuws'*.

A lot of media attention on 11 February 2016.



Jo van den Brand at the press conference.

Media coverage at a record high.

But 11 February 2016 was only the beginning of what became an entire year of continuous media attention and countless outreach events surrounding gravitational waves. For example, long interviews with Jo van den Brand were published about how he had experienced the months between the detection of the first signal in September 2015 and the public announcement in February 2016. The press also extensively covered the second detection of gravitational waves announced in June 2016, and the future plans for a possible new gravitational wave observatory called Einstein Telescope. With never-ending enthusiasm, Nikhef researchers appeared in many science cafés, attended public debates and discussions, and talked at symposia and other events throughout the country.

Chris Van Den Broeck in *'RTL Nieuws'*.

Right-to-left: Van Den Broeck, Van den Brand and Nelemans in *'De Wereld Draait Door'*.

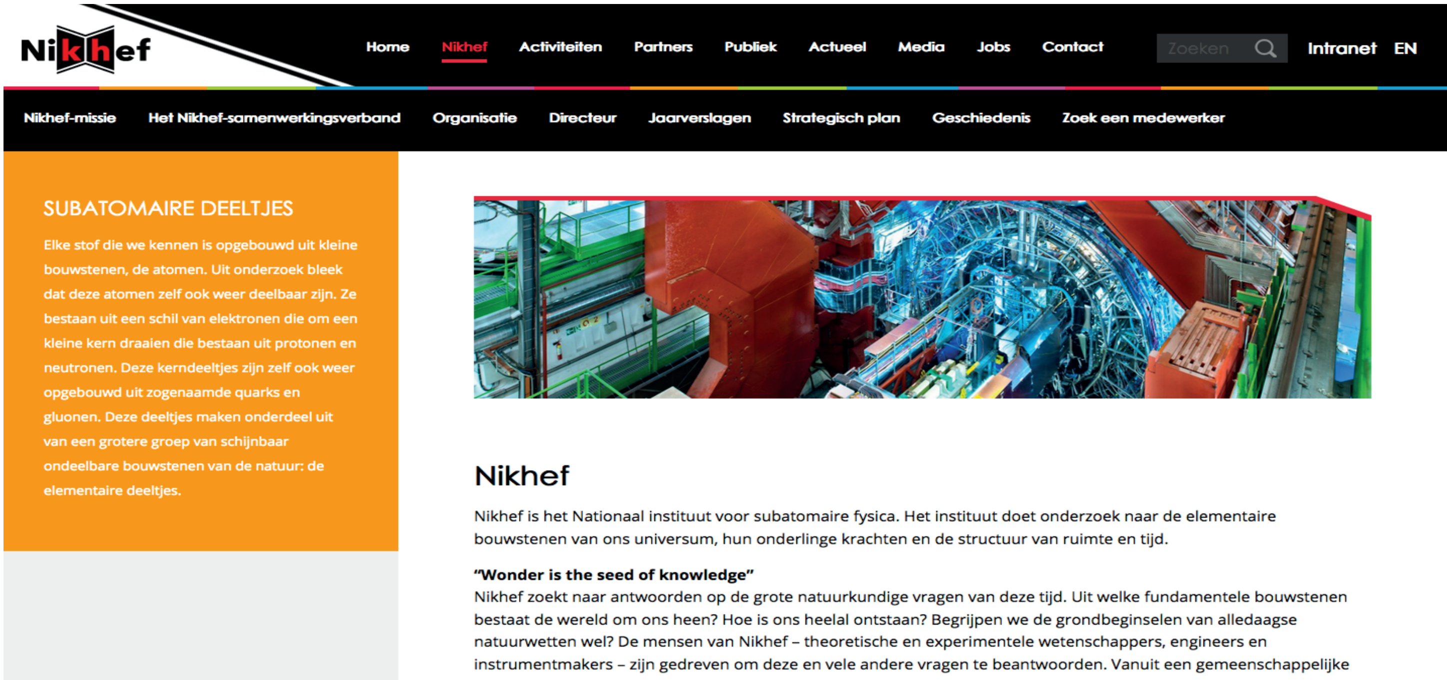
Young visitors enjoy a 3D film at the Open Day.

Hundreds of enthusiastic visitors at Open Day Nikhef

On 1 October, Nikhef again welcomed hundreds of visitors for its annual Open Day. Of course, many visitors were especially interested in finding out more about the first detection of gravitational waves, that many Nikhef researchers had played an important role in. But also the quest for dark matter, the various LHC experiments and all the other research programmes at Nikhef attracted many people. As every year, the short lectures for adults were as well-attended as the different workshops and the particle treasure hunt for children. Throughout the whole afternoon, and everywhere in the Nikhef building, many animated discussions took place between visitors of all ages and all the Nikhef employees who were happy to explain their work. The Open Day is organised annually together with the other institutes, universities and companies at Amsterdam Science Park as part of the *'Weekend van de Wetenschap'* (Weekend of Science).

Website and social media

In 2016 the website www.nikhef.nl was completely modernised with a new design, navigation and content management system. It is a worthy new look for the first website in the Netherlands and the third website in the world. On social media, Nikhef gained a lot of attention, especially on and around the announcement of the first direct detection of gravitational waves on 11 February 2016. This was in the shape of an increasing number of followers, likes and retweets on Twitter and likes on Facebook. Our efforts on Instagram increased throughout the end of the year and into the new year.

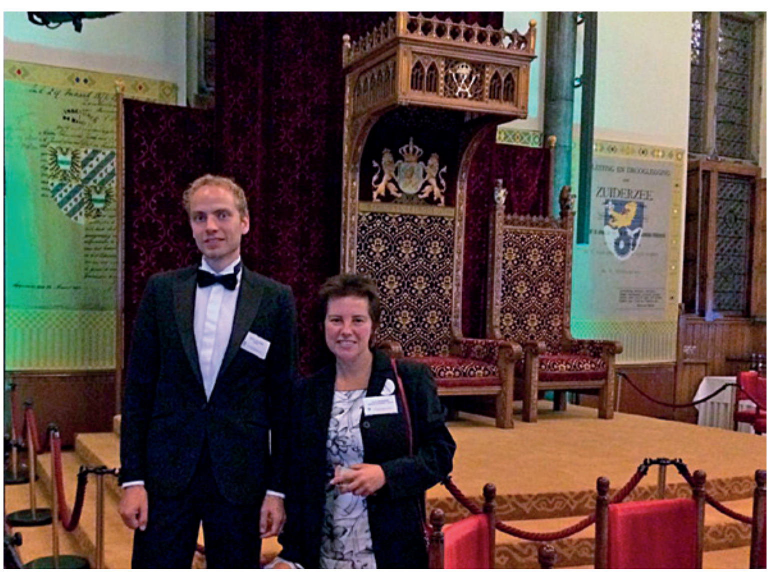


Boerhaave Museum receives historic pieces Nikhef

Nikhef has transferred a part of its historical archives to the Boerhaave Museum in Leiden. From the research conducted in the last 70 years, Nikhef has preserved a number of objects and documents for the purpose of science history. A number of these objects and documents including mock-ups, parts of installations and several smaller items have now been donated to the museum. They are included in the museum's collection and will occasionally be on display for the general public. Furthermore, in this way they remain available for future research.

Willem van Leeuwen (middle) and Jan Visschers (right) explain the 'BOL'-system that was donated to the Boerhaave Museum.

Nikhef researchers give lectures at many outreach events



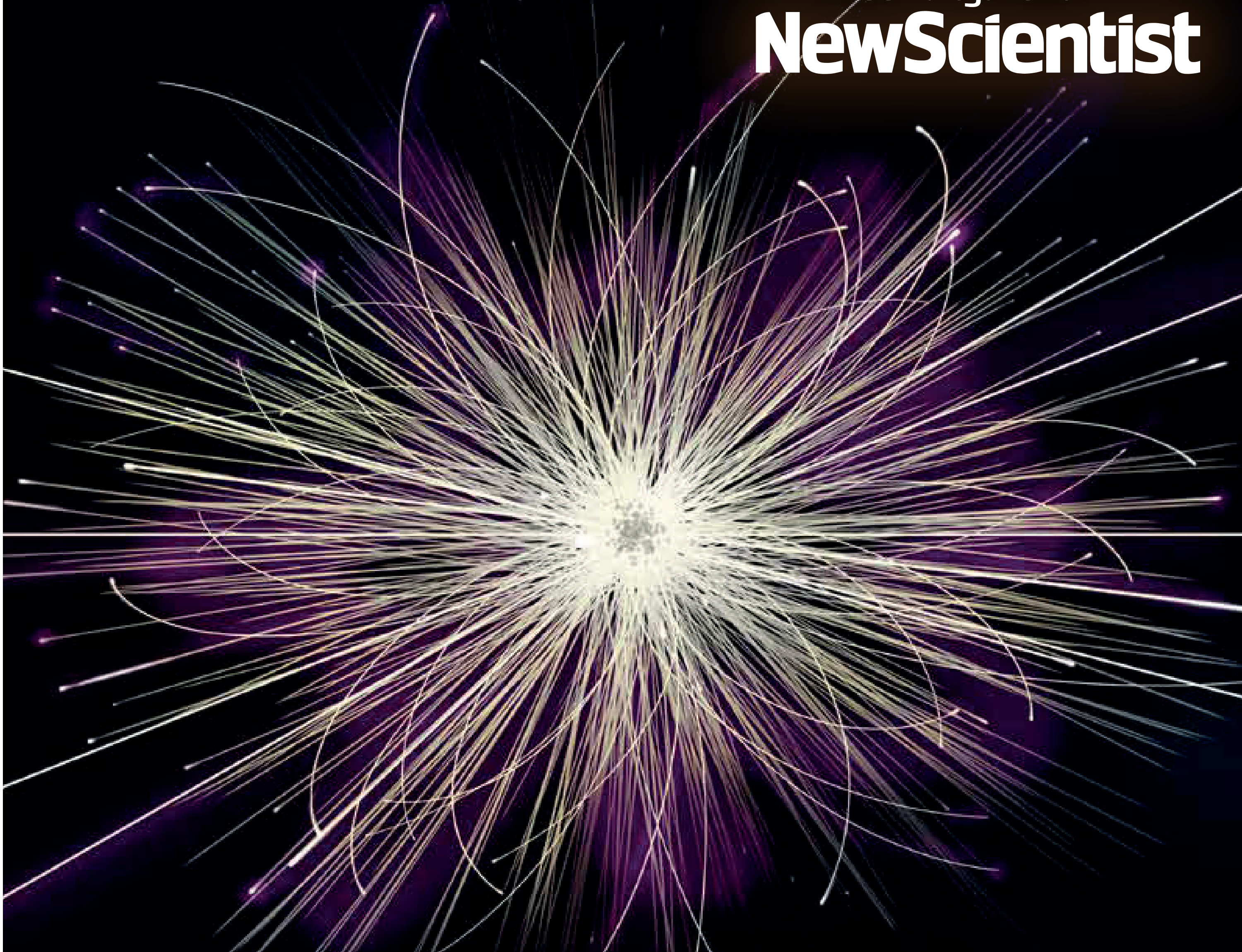
Olga Igonkina and Jacco de Vries took part in the *'Avond van Wetenschap & Maatschappij 2016'*.
This annual event to which a select group of 275 people from all parts of science, economy, politics, culture, media and sports is invited, emphasises the importance of fundamental research to society. Olga Igonkina and Jacco de Vries led the discussion on the impact that not yet fully understood processes in our universe have on our past and our future.

For a full list of outreach talks by Nikhef researchers please refer to the Appendix of the Annual Report on the Nikhef website.

Nikhef

Nederlandstalige editie | december 2016 | **NewScientist.nl**

een uitgave van **NewScientist**



Op jacht naar de kleinste deeltjes

A special supplement entirely dedicated to Nikhef was distributed together with the Dutch December issue of the New Scientist. This Nikhef special featured a broad number of aspects of the institute, from highlights and milestones since its foundation in 1975, to the latest results of Nikhef's research programmes and interviews with Nikhef researchers and alumni. The New Scientist has nearly 20.000 subscribers in the Netherlands.
For a more extensive list of articles about Nikhef in the Dutch media please refer to the Nikhef website.

mede mogelijk gemaakt door Nikhef

Education

Nikhef attaches great importance to inspiring and training young people. To this end, Nikhef offers various programmes for secondary school students and their teachers, as well as a thorough education for master and PhD students.

Programmes for secondary schools

For secondary school students, Nikhef offers many opportunities to get introduced to particle and astroparticle physics, such as carrying out their *'profielwerkstuk'* at Nikhef, following a one-day International Masterclass on Particle Physics or the Masterclass International Cosmic Day , or visiting Nikhef with a school group. Teachers can follow an annual four day Dutch CERN Teachers programme organised by Nikhef and CERN, or a teacher-in-research programme (*'Leraar in Onderzoek'*) made possible by FOM and Nikhef.

Programme	Participants
'Profielwerkstuk'	22
International Masterclass Particle Physics	50
Cosmic Day	17
Visiting Nikhef	more than 100
Dutch CERN Teachers Programme	20
Teachers in research (LiO)	7

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 particle physics research done at Nikhef. In the first year, the programme typically consists of lectures on Particle and Astroparticle Physics, as well as advanced experimental methods. The various aspects of experimental particle physics are combined in a semester-long project, and the past academic year a floating (and self-adjusting) muon scintillation detector was built (see photo top).

There were a few changes in the programme: the VU and UvA MSc programmes were officially joined in a joint degree at the beginning of the 2016/2017 academic year. Perhaps as a result, UvA/VU's GRAPPA programme also saw a record-setting 33 first-year MSc students enter this year, all of these students follow Nikhef's particle physics lectures and about half are expected to also do a research project at Nikhef. The year-long research project is done in the second year of the Master. Nearly 30 students graduated on Nikhef-research-related projects in 2016 (see appendix).

Research School Subatomic Physics

Nikhef provides academic training for all its PhD students through the Research School Subatomic Physics (*'Onderzoeksschool Subatomaire Fysica'*, OSAF). OSAF organises three topical lecture series and an annual summer school every year.

In February 2016, the University of Groningen (RUG) entered into the Nikhef partnership. At RUG, 10 PhD students graduated in 2016 on Nikhef-related research. As of 2017, the RUG PhD students will also join OSAF. For 2016, they are not yet included in the OSAF statistics below.

In 2016, 28 new students started their PhD with OSAF, and 28 students from OSAF obtained their PhD degrees. In total, 96 students were registered with the research school in 2016.

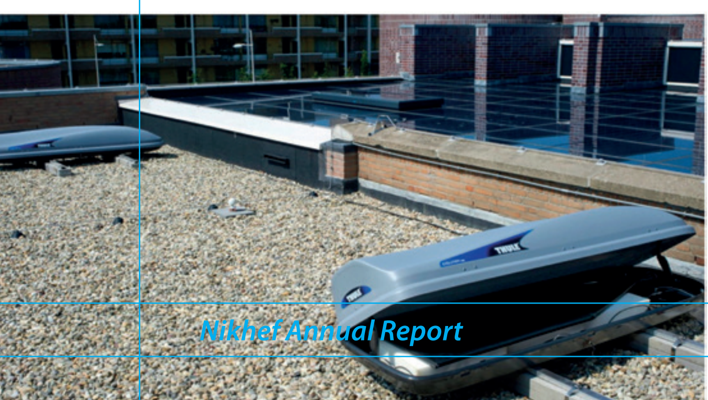
HiSPARC
Big data for high-schools

Historically, cosmic ray research has been at the front in the quest for new physics. Extremely high energy cosmic ray particles from yet undefined sources, the (GZK) cut-off at the high end of the energy spectrum and spallation of particles due to interactions with photons in our solar system (GZ), continue to pose intriguing scientific questions. The HiSPARC (High School Project on AstroPhysics Research with Cosmics) experiment (http://www.hisparc.nl/) provides secondary school students and teachers hands-on opportunities to participate in this challenging field of research.

HiSPARC hosts an extensive network of ~140 cosmic ray detection stations (Fig. 1) in the Netherlands, UK and Denmark. Stations are maintained by high-schools, universities and science institutes. The (irregular) geometry of the network is defined by the geographic location of participants and covers station to station distances up to ~1,000 km (Fig. 2a). The number of participating high-schools is steadily increasing (Fig. 2b).

Data collected by each individual station is send through internet to a central data server at Nikhef. After initial processing, this data becomes publicly available. There are several platforms allowing data access ranging from downloading data in tables ready for analyses with standard spread-sheet programs, based on the Python programming language, for interactive analysis. Recently, Python Notebooks have been explored accumulating into a collaboration with SurfSARA. As of early 2017, SurfSARA will sponsor and host a public Python NoteBook server for HiSPARC. NoteBooks have the advantage of integrating a Python programming environment with documentation and graphical presentation of results. Template analyses can be tuned to the level of the student. The student may introduce modifications and store private copies on the server. With a central NoteBook server there is no need to install software locally. All programs are executed from the local browser. The development of NoteBooks receives financial support from the SNS outreach fund (two 0.2 fte teacher positions).

Figure 1. A HiSPARC station consists of 2 or 4, 100 × 50 × 2 cm scintillator detectors and a GPS unit for precise timing measurements. The 4-scintillator set-up allows for local reconstruction of zenith and azimuth angles of cosmic ray airshowers



Since 2004, HiSPARC supports a 'Teacher in Research' (*Leraar in Onderzoek*) programme. Also in 2016 NWO/FOM subsidised 0.2 fte teacher positions enabling them to focus one year long on cosmic ray research (Fig. 3). Teachers present their work at group meetings while their research is also documented in yearly report.

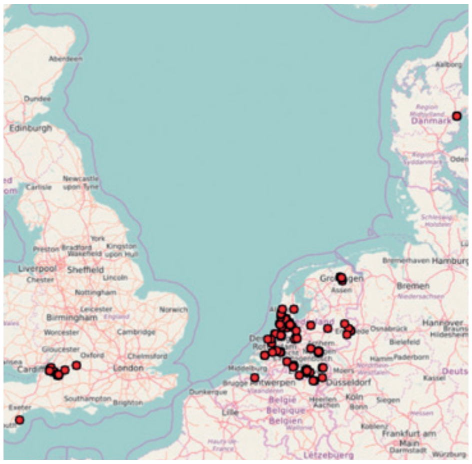


Figure 2a. Left: Overview cosmic ray stations in the HiSPARC network (early 2016).

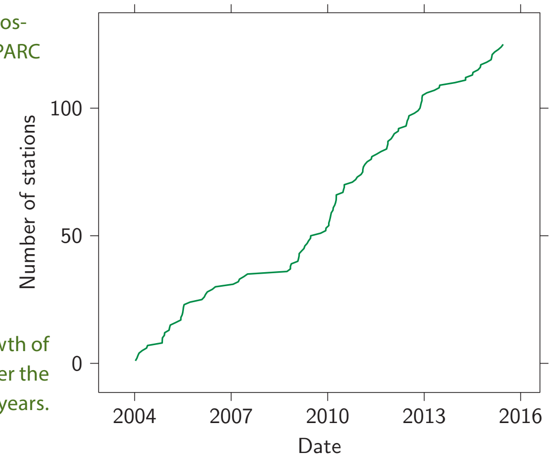


Figure 2b. Right: Growth of the HiSPARC network over the years.

As HiSPARC collects large amounts of data on cosmic air showers. Systematic studies can be performed. The experiment basically registers the numbers of charged particles belonging to a single shower arriving at various stations and their arrival times. Using statistical models of air showers these data allow to estimate properties such as the total number of particles in the shower, its direction and the energy carried by the primary cosmic ray particle. In his PhD thesis, H. Montanus has constructed and analysed models for the longitudinal development of showers in the atmosphere: how many particles of which energy one can expect at a given depth in the atmosphere after the first interaction. He also analysed the corresponding lateral distribution of particles as measured by the number of hits registered by an array of HiSPARC stations. Using the insights gained he has investigated the possibility to observe signs of hadronic jets in the particle distribution. These would manifest themselves by multiple cores in the particle density at ground level. Monte Carlo studies show however, that most of the time these multiple cores cannot be distinguished from statistical fluctuations in the number of particles registered by stations at sea level.

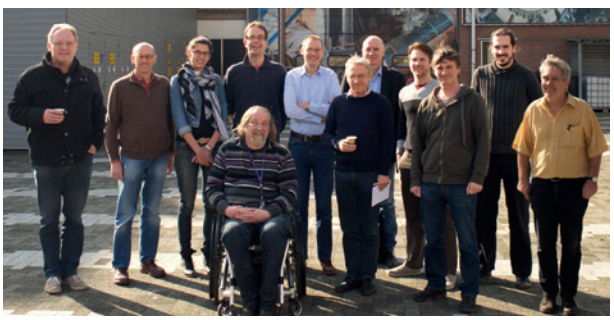
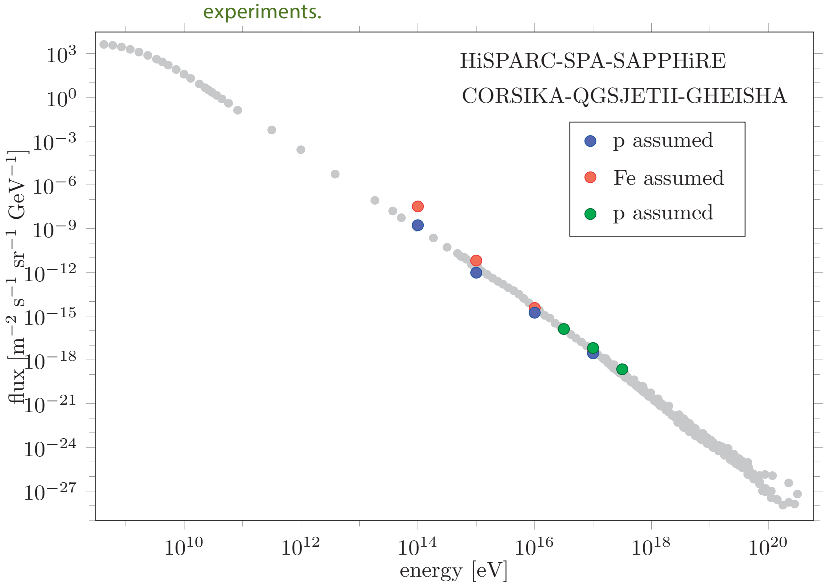


Figure 3. Amsterdam Nikhef HiSPARC team (staff, teachers and PhD students), June 2016.

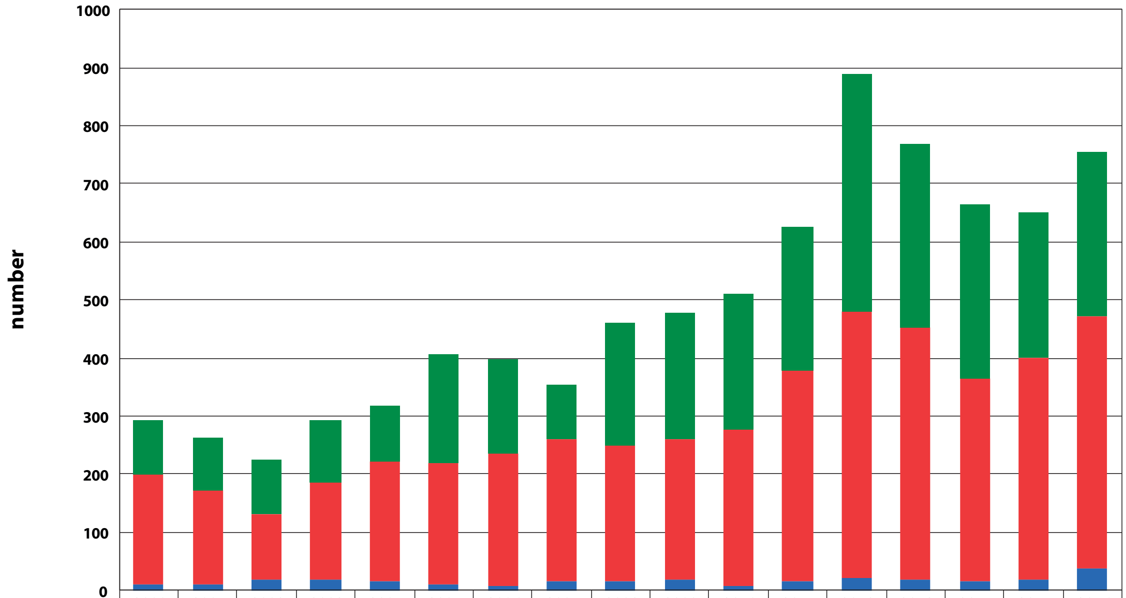
By comparing the HiSPARC data with shower simulations the rate of primary particles of various initial energies as measured by the HiSPARC experiment was determined. The results are plotted in Fig. 4, which also shows the data of other experiments for comparison. The study was financially supported by the NWO programme enabling secondary school teachers to obtain a PhD degree.

Figure 4. Cosmic ray energy spectrum. Coloured: fluxes as derived from the reconstruction of showers observed at the Science Park Amsterdam site of HiSPARC. Grey: combined fluxes by previous experiments.



Output

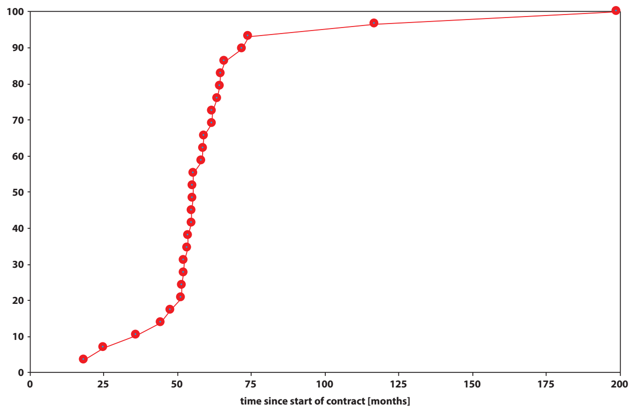
The scientific output of the institute can be measured in the number of publications, talks and even more important, in the number of PhD theses. In the output we see fluctuations in time depending on whether accelerators are active and experiments take data. The Large Hadron Collider (LHC) started delivering physics data again on 3 June 2015. Analysis of these data has started. The detection of gravitational waves is accompanied by a boost of papers in that field. The expansion of Nikhef with the Van Swinderen Institute has led to an clear increase in the number of PhD theses.



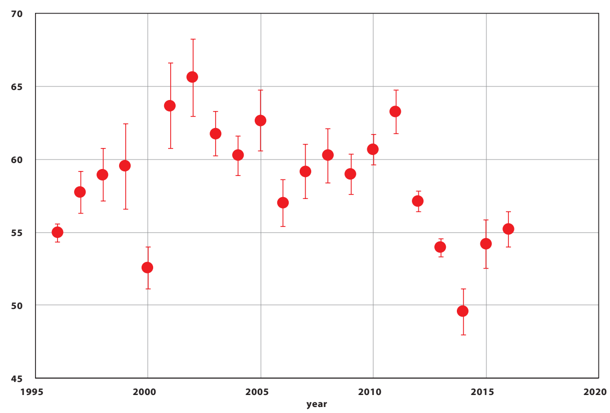
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Talks	92	91	95	108	97	186	162	93	212	215	231	248	410	316	298	251	283
Publications	190	163	113	168	207	209	228	246	234	243	270	361	458	435	351	380	434
Theses	11	10	18	18	15	10	9	15	15	18	8	17	22	18	15	20	38

Nikhef's scientific output in the last 17 years. See also online Appendix.

Also in the PhD duration we see yearly fluctuations, depending on the above mentioned experimental conditions, but also depending on the internal policies of the collaborations for analysis and publication. Outliers in the distribution are related to the difficulty of finishing a thesis when already in a new job.



Fraction of PhD students working at Nikhef that graduated in the year 2016 as a function of time since the start of their thesis contract (VSI not included). The median PhD duration is 55.2 months.



Median PhD duration of Nikhef PhD students since 1996 as a function of graduation year. The error bars represent the median absolute deviation (MAD)/√(n-1).

PhD Theses

Thomas Zojer
Non-relativistic supergravity in three space-time dimensions
Rijksuniversiteit Groningen, 4 January 2016
Promotor: E.A. Bergshoeff

You Zhou
Anisotropic flow and flow fluctuations at the Large Hadron Collider
Universiteit Utrecht, 6 January 2016
Promotor: R. Snellings, Copromotor: P. Christakoglou

Joern Mahlstedt
Search for excited leptons with the ATLAS detector
Universiteit van Amsterdam, 21 January 2016
Promotor: O.B. Igonkina, Copromotor: P.J. de Jong

Kimberley Keri Vos
Symmetry violation in weak decays
Rijksuniversiteit Groningen, 5 February 2016
Promotores: R.G.E. Timmermans, H.W.E.M. Wilschut

Daniela Remenska
Bringing model checking closer to practical software engineering
Vrije Universiteit Amsterdam, 8 February 2016
Promotor: H.E. Bal, Copromotores: J.A. Templon, T.A.C. Willemse

Nikolaos Karastathis
Determination of spin and parity of the Higgs boson in the $WW^* \to e\nu\mu\nu$ decay channel with the ATLAS detector
Universiteit Twente, 25 February 2016
Promotores: B. van Eijk, G. Tsipolitis,
Copromotor: P. Ferrari

Tiago Jose Nunes da Silva
Approaching conformality in non-Abelian gauge theories
Rijksuniversiteit Groningen, 26 February 2016
Promotor: E. Pallante

Martijn Reicher
Digital calorimetry using Pixel sensors
Universiteit Utrecht, 7 March 2016
Promotor: T. Peitzmann, Copromotor: G.J.L. Nooren

Misha Veldhoen
Identified particle yield associated with a high-p_T trigger particle at the LHC
Universiteit Utrecht, 14 March 2016
Promotor: T. Peitzmann, Copromotor: M. van Leeuwen

Pieter Christiaan van der Deijl
Double parton interactions with a $Z + 2$ jet signature in proton-proton collisions at the LHC
Universiteit Twente, 16 March 2016
Promotor: B. van Eijk

Andrea Dubla
Elliptic flow at different collision stages
Universiteit Utrecht, 6 April 2016
Promotor: R.J.M. Snellings, Copromotor: A.G. Grelli

Siim Tolk
Discovery of rare B decays
Rijksuniversiteit Groningen, 8 April 2016
Promotores: A. Pellegrino, F. Dettori

Stefan Jansen
Radio for the masses: Cosmic ray mass composition measurements in the radio frequency domain
Radboud Universiteit Nijmegen, 13 April 2016
Promotor: S.J. de Jong,
Copromotor: C.W.J.P. Timmermans

Giuseppe D'Ambrosi
Dynamics of Extreme-Mass-Ratio binaries. Extraction of gravitational waves beyond Last Stable Orbit and introduction of spin in the particle limit
Vrije Universiteit Amsterdam, 21 April 2016
Promotores: J.F.F. van den Brand, J.W. van Holten

PhD defense Jeroen van Leerdam – procession of professors.

Sandro Bjelogrlic
Azimuthal angular correlations of D-mesons and charged particles with the ALICE detector at the LHC
Universiteit Utrecht, 4 May 2016
Promotor: R.J.M. Snellings, Copromotor: A. Mischke

Tino Michael
Light at the end of the shower: an all-flavour neutrino point-source search with the ANTARES neutrino telescope
Universiteit van Amsterdam, 13 May, 2016
Promotor: P.M. Kooijman, Copromotor: A.J. Heijboer

Jacoba Roelien Meinema
Obtaining ultracold molecules through Stark deceleration and laser cooling
Rijksuniversiteit Groningen, 13 May 2016
Promotores: S. Hoekstra, K.H.K.J. Jungmann

Domenico Bonocore
Next-to-soft factorization and unitarity in Drell-Yan processes
Universiteit van Amsterdam, 18 May, 2016
Promotor: E.L.M.P. Laenen, Copromotor: C.D. White

Jeroen van Leerdam
Measurement of CP violation in mixing and decay of strange beauty mesons
Vrije Universiteit Amsterdam, 18 May, 2016
Promotor: H.G. Raven, Copromotor: M.H.M. Merk

Valentin Reys
Quantum black hole entropy and localization in supergravity
Universiteit Utrecht, 13 June 2016
Promotor: B.Q.P.J. de Wit, Copromotor: S. Murthy

Marco Scalisi
Inflation, universality and attractors
Rijksuniversiteit Groningen, 13 June 2016
Promotores: D. Roest, E.A. Bergshoeff

Victor Alejandro Penas
Properties of double field theory
Rijksuniversiteit Groningen, 21 June 2016
Promotores: E.A. Bergshoeff, D. Roest

Satish Kumar Saravanan
Spin dynamics in general relativity
Universiteit Leiden, 7 July 2016
Promotor: J.W. van Holten

Pieter Norbert Yvonne David
Search for exotic long-lived particles with the LHCb detector
Vrije Universiteit Amsterdam, 7 July 2016
Promotor: M. Merk, Copromotor: W.D. Hulsbergen

Amita Mohanty
Lifetimes, level energies and light shifts in a single trapped Ba^+ Ion
Rijksuniversiteit Groningen, 9 September 2016
Promotor: K.H.K.J. Jungmann
Copromotor: L. Willmann

Roel Andringa
Newton-Cartan gravity revisited
Rijksuniversiteit Groningen, 23 September 2016
Promotor: E.A. Bergshoeff

Koen Pieter Oussoren
Reflecting on Higgs:spin and parity measurement in the $H \to WW \to e\nu\mu\nu$ channel
Universiteit van Amsterdam, 27 September 2016
Promotor: S.C.M. Bentvelsen, Copromotor: P.M. Kluit

PhD defense Jeroen van Leerdam – reception afterwards.

Hartger Weits
Looking for lepton flavour violation with the ATLAS detector. A search for $Z \rightarrow \tau\ell$ decays
Universiteit van Amsterdam, 21 September 2016
Promotores: S.C.M. Bentvelsen, O.B. Igonkina

Andrea Signori
Flavor and evolution effects in TMD phenomenology; Manifestation of hadron structure in high-energy scattering processes
Vrije Universiteit Amsterdam, 17 October 2016
Promotor: P.J.G. Mulders, Copromotor: M. Radici

Guus Anton van Aar
On the nature and origin of ultra-high-energy cosmic rays
Radboud Universiteit Nijmegen, 19 October 2016
Promotor: S.J. de Jong,
Copromotor: C.W.J.P. Timmermans

Robbert Johannes Rietkerk
Unitarity methods and on-shell particles in scattering amplitudes
Universiteit van Amsterdam, 19 October 2016
Promotor: E.L.M.P. Laenen, Copromotor: K.J. Larsen

Nikolaus Axel Naumann
Measurement of $\sigma(pp \rightarrow Z) \times BR(Z \rightarrow bb)$ at $\sqrt{s} = 1.96$ TeV
Radboud Universiteit Nijmegen, 24 October 2016
Promotores: S.J. de Jong, F. Filthaut

Redmer Alexander Bertens
Path length dependence of jet quenching measured with ALICE at the LHC
Universiteit Utrecht, 31 October 2016
Promotores: R.J.M. Snellings, M. van Leeuwen

Panagiotis Christos Tsopelas
A silicon pixel detector for LHCb
Vrije Universiteit Amsterdam, 21 November 2016
Promotores: M.H.M. Merk, E.N. Koffeman,
Copromotor: S. Bentvelsen

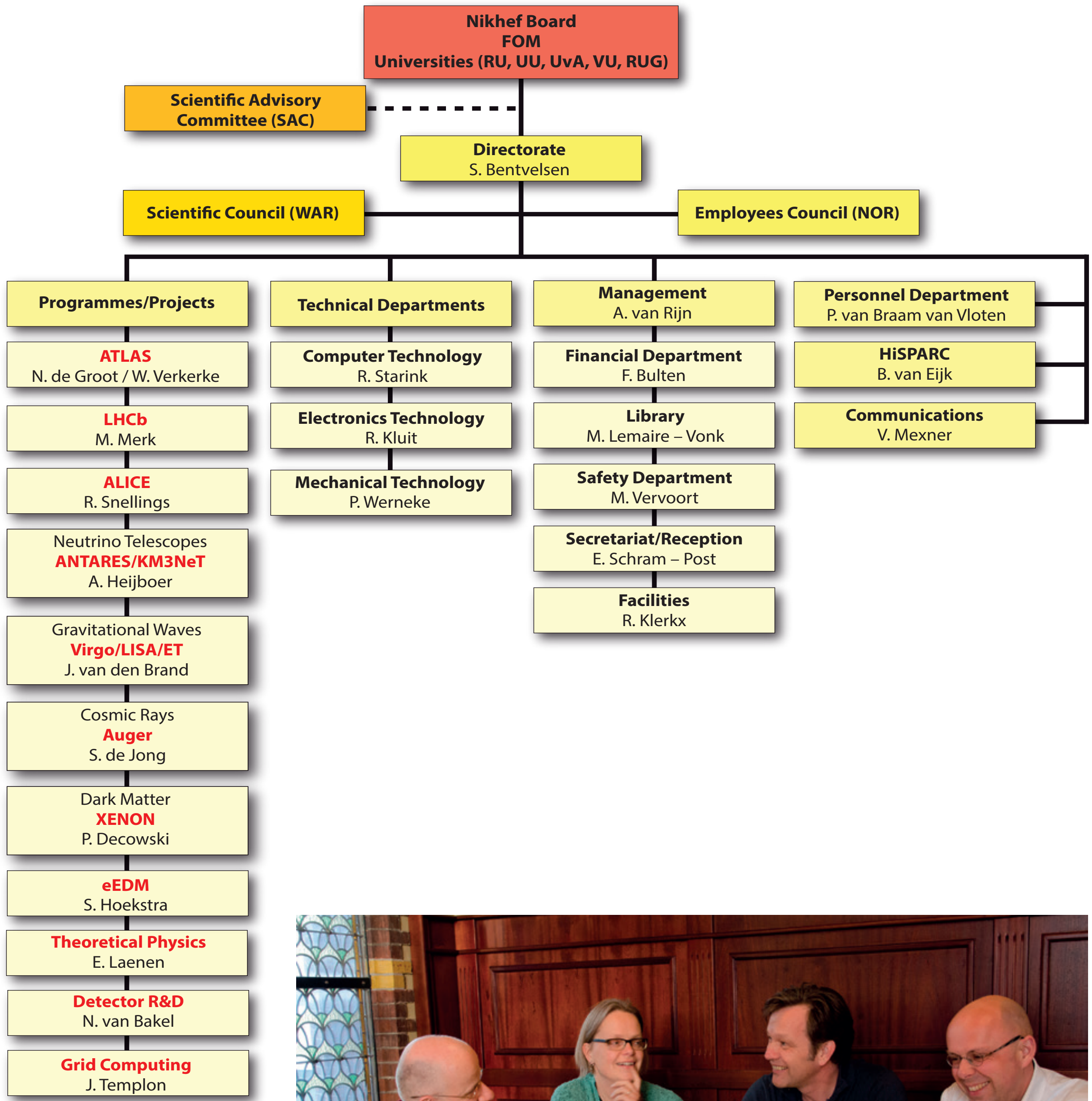
Ingrid Deigaard
Searches for coloured supersymmetry with ATLAS at $\sqrt{s} = 8$ TeV, 13 TeV, and 14 TeV
Universiteit van Amsterdam, 30 November 2016
Promotor: P.J. de Jong,
Copromotor: M. Vranjes Milosavljevic

Auke Sytema
Testing Lorentz invariance in β decay
Rijksuniversiteit Groningen, 5 December 2016
Promotor: H.W.E.M. Wilschut,
Copromotor: C.J.G. Onderwater

Emilia Leogrande
Jet-like two-particle correlations in p-Pb collisions
Universiteit Utrecht, 7 December 2016
Promotor: R.J.M. Snellings,
Copromotor: J.F. Grosse-Oetringhaus

Michalis Agathos
The swan song of a neutron star binary: Fundamental physics and astrophysics with gravitational waves from compact binary coalescence
Vrije Universiteit Amsterdam, 20 December 2016
Promotor: J.F.J. van den Brand,
Copromotor: C. Van Den Broeck

Organigram



The Nikhef management team; from left to right: Arjen van Rijn, Els Koffeman, Stan Bentvelsen, and Pieter van Braam van Vloten.

Nikhef Organization

Nikhef Board: C. Gielen *(chair, Radboud University Nijmegen)*, J. de Kleuver *(secretary, FOM)*, H. Irth *(VU University Amsterdam)*, N. Lopes Cardozo *(FOM)*, G. van Meer *(Utrecht University)*, K. Maex *(University of Amsterdam)*, C. Hooijer *(FOM)*

Management Team: S. Bentvelsen, P. van Braam van Vloten, E. Koffeman, A. van Rijn

Scientific Advisory Committee (SAC): H. Abramowicz *(University of Tel Aviv, Tel Aviv)*, N. Glover *(IPPP, Durham)*, J. Mnich *(DESY, Hamburg)*, T. Nakada *(EPFL, Lausanne)*, A. Rubbia *(chair, ETH, Zürich)*, J. Schukraft *(CERN, Geneva)*, C. Spiering *(DESY Zeuthen, Berlin)*

Employees Council (NOR): L. Brenner, R. Hart *(secretary)*, J.J. Keijser *(vice chair)*, N. Rem, B. Schellekens, F. Schreuder *(vice secretary)*, H. Snoek, G. Visser, J. Visser *(chair)*

CERN Contact Committee (Nikhef members only): S. Bentvelsen, S. de Jong *(chair)*, N. de Groot, E. Laenen *(secretary)*, M. Merk, Th. Peitzmann

Scientific Council (WAR): S. Bentvelsen, D. Boer, C. van den Broeck, S. Caron, A.P. Colijn, W. Hulsbergen, P. de Jong, M. van Leeuwen, A. Mischke, G. Onderwater, Th. Peitzmann *(chair)*, M. Postma, G. Raven, A. van Rijn *(secretary)*, D. Samtleben, H. Snoek, C. Timmermans, N. Tuning *(staff meeting)*, I. van Vulpen

Programme Leader Consultation (OPL): N. van Bakel, S. Bentvelsen, E. bergshoeff, P. van Braam van Vloten, J. van den Brand, P. Decowski, N. de Groot, A. Heijboer, S. Hoekstra, P. de Jong, S. de Jong, E. Koffeman, E. Laenen, M. Merk, T. Peitzmann, A. van Rijn, R. Snellings, J. Templon, W. Verkerke

Research School Subatomic Physics (OSAF) – Education Committee: S. Bentvelsen *(Nikhef, UvA)*, J. Berger *(secretary)*, J. van den Brand *(VU)*, P. van Braam van Vloten *(Personnel)*, P. Decowski *(UvA)*, B. van Eijk *(Nikhef, UT)*, R. Fleischer *(VU)*, N. de Groot *(RU)*, O. Igonkina *(Nikhef, RU)*. P. de Jong *(UvA)*, S. de Jong *(RU)*, E. Koffeman *(UvA)*, M. Merk *(Nikhef, VU)*, P. Mulders *(VU)*, Th. Peitzmann *(UU)*, A. Pellegrino *(VU)*, G. Raven *(VU)*, R. Snellings *(UU, chair)*

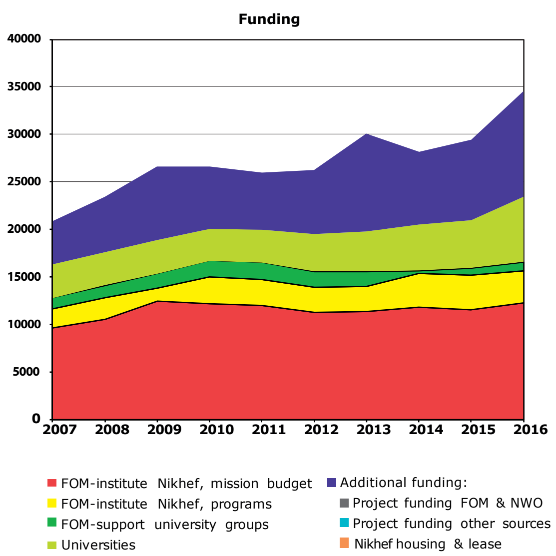
Overview of Nikhef personnel in fte (31-12-2016)	
I – Scientific groups (fte; institute & university groups)	
Permanent Scientific staff	71.3
PhD students	100.4
Post-docs	28.8
Total I	**200.5**
II – Management, technical/engineering and general support (fte; institute)	
Management team	
Director	1.0
Institute manager	1.0
Personnel manager	1.0
Manager Scientific Instrumentation	0.5
Subtotal	*3.5*
Technical/engineering support	
Electronics technology	22.9
Computer technlogy	19.5
Mechanical technology	27.5
Subtotal	*69.8*
General support	
Financial administration	3.8
Personnel/HRM administration	1.0
Library	0.6
Facilities & Datacenter	7.6
Secretariat & reception	3.9
PR & communication	2.6
Occupational health & safety	2.0
Staff	3.9
Subtotal	*25.4*
Total II	**98.7**
Total I & II	**299.2**
III – Other groups (number of persons)	
Guests (researchers, retired staff)	107
Master students	27
Apprentices	11

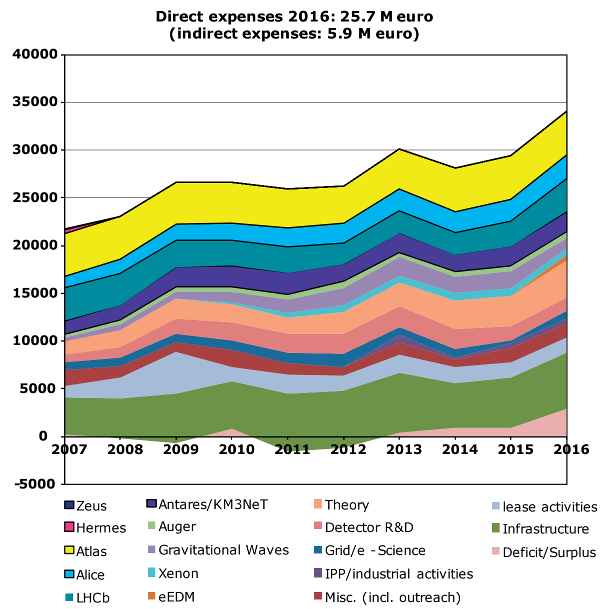
Funding & Expenses

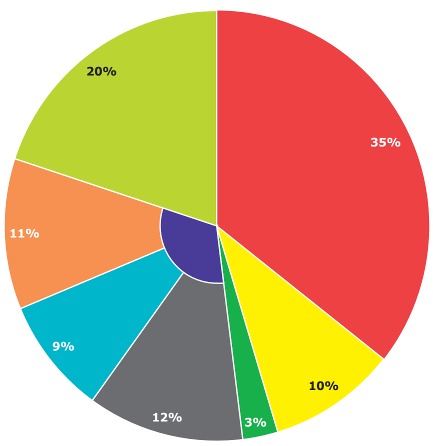
The 2016 funding level of the Nikhef collaboration is higher than ever: 34.5 M€ (versus 29.5 M€ in 2015). Almost half of this increase can be attributed to the university partners, in particular to the accession of the University of Groningen (Van Swinderen Institute – VSI) to the Nikhef collaboration. The remainder of the increase is due to recent successes in the various funding channels. A new FOM-programme has been acquired in 2016, by Steven Hoekstra from VSI, for the eEDM activity. This programme funding will show in the figures as of 2017.

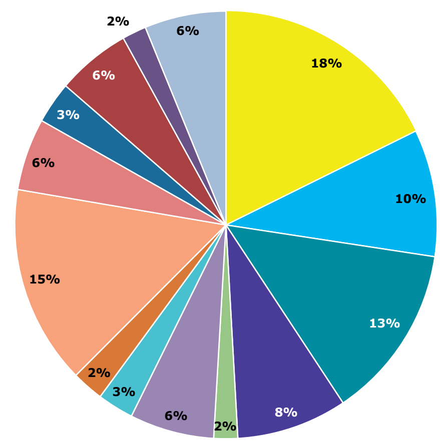
The expenses for accelerator-based particle physics (ATLAS, LHCb and ALICE, together 41% of direct expenses) have further increased, due to the ramp up of instrumentation activities for the detector upgrades. The astroparticle physics activities, for which construction activities are still considerable, have consumed about 19% of direct expenses. The eEDM line is currently 2%, but will increase thanks to the new programme funding. The enabling activities (computing, detector R&D and particularly theory) comprise 24% of expenses, whilst industrial activities, outreach and lease activities make out the remainder (14%) of the direct costs.

Budget and grants labelled as investments are not included in the graph, in particular the investments in the KM3NeT detector and the LHC detector upgrades, in 2016 together budgeted at about 5 M€.









Glossary

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–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.

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.

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.

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.

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.

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
A subtle effect observed in the decays of certain particles that 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.

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.

Electron
See Particles.

eLISA (evolved LISA)
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.

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 ($\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$...). 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.

FTE (Full Time Equivalent)
Unit of manpower.

Gluon
See Particles.

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.

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,

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.

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 prototype that is currently in the development phase.

Meson
See Particles.

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.

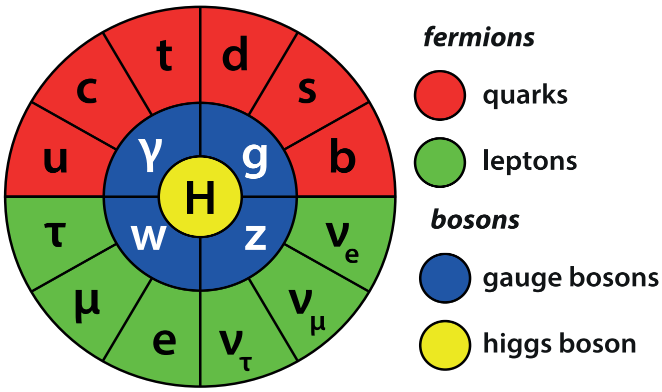
Neutrino
Uncharged, weakly interacting lepton, most commonly produced in nuclear reactions such as those in the Sun. There are three known flavours of neutrino, corresponding to the three flavours of leptons. Recent experimental results indicate that all neutrinos have tiny masses (see also Particles).

NNLO (Next–to–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.

Nucleon
The collective name for protons and neutrons.

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 gold 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.

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

Spin
Intrinsic angular momentum of a particle.

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

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.

SURFnet
Networking organization in the Netherlands.

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

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

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.

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.

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.

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.