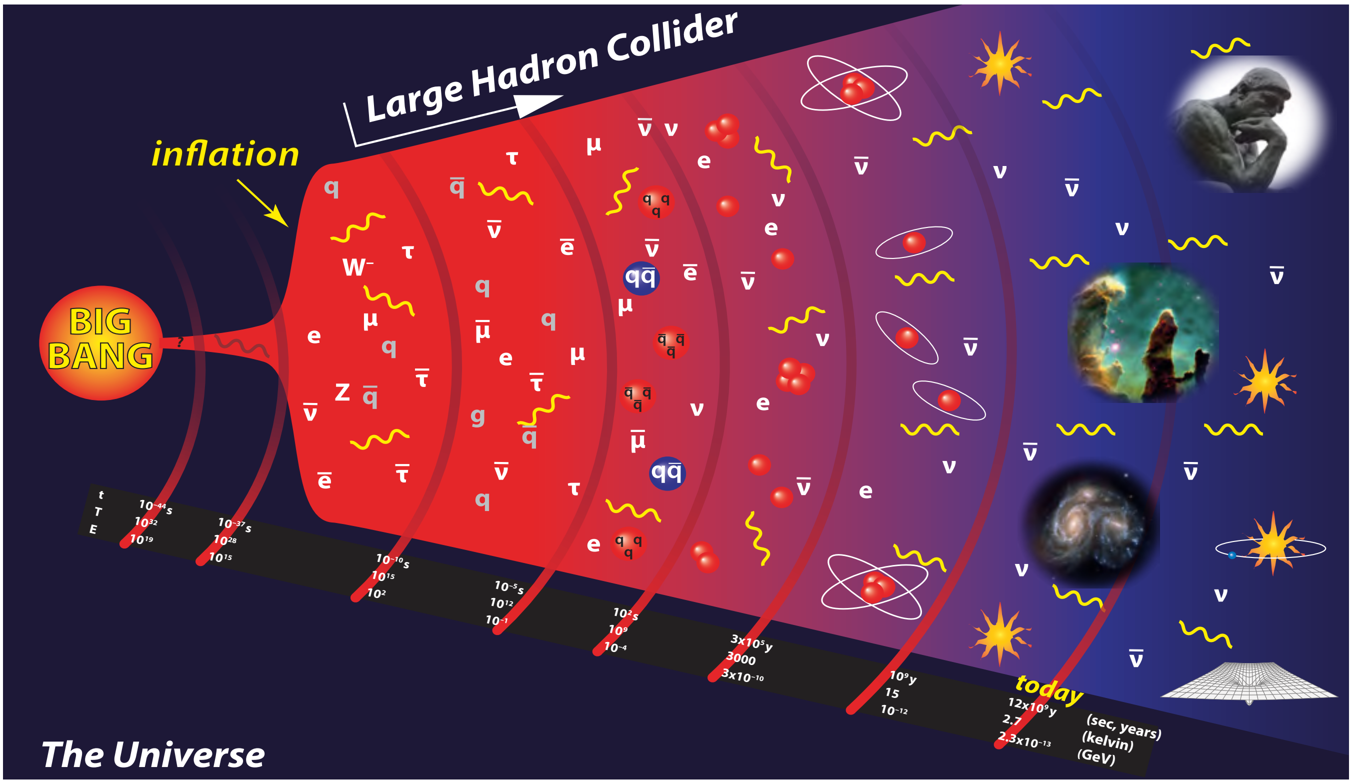
Application form
National Roadmap for Large-Scale Research Facilities 2013

Dutch contributions to the detector upgrades of the Large Hadron Collider experiments at CERN



"The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further New Physics at the energy frontier. The LHC is in a unique position to pursue this programme. Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma."

2013 European Particle Physics Strategy

General information

Contents

Scientific and general interest magazines shared the excitement after the announcement of the discovery of the Higgs particle (The Economist 7-7-2012) and acknowledged the importance when reviewing the break-throughs of the year (Science 12-2012).

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Abstract

Summary

The *Large Hadron Collider* (LHC) at CERN is the world's most powerful particle accelerator, installed in a 27 km circumference underground ring straddling the border between Switzerland and France near Geneva. Two counter-rotating beams of particles are accelerated to world-record energies to collide at four locations along the ring. The collision points are viewed by huge particle detectors (ATLAS, ALICE, CMS and LHCb), to study elementary particles and their interactions. The first years of LHC operation were very successful, with as undisputed highlight the discovery of the Higgs particle in 2012. Presently, the LHC accelerator complex is being refurbished to allow operation at its full design energy and intensity. After completion in 2015, the LHC will be in an excellent position to unveil the hitherto unexplored TeV (10^{12} eV) energy scale. The LHC discovery potential includes: the detailed properties of the just-discovered Higgs particle, which is supposed to be responsible for all known elementary particle masses; the nature of the matter-antimatter differences, essential to explain the matter dominance in the Universe today, 13.8 billion years after the Big Bang; the structure of the quark-gluon plasma, a state of matter assumed to have existed briefly after the Big Bang; and last, but not least, proof of physics beyond the so-called Standard Model, the immensely successful theoretical framework that accurately describes a wealth of experimental observations, but amongst others falls short to explain the nature of the mysterious dark matter in the Universe. Because of this tremendous discovery potential, the LHC is consistently ranked as the top-priority project in particle physics.

As a founding member of CERN in 1954, the Netherlands has a strong track record at CERN and in particle physics. Dutch scientists have held top management positions at CERN, notably as Director General and as Research Director. Simon van der Meer's 1984 Nobel prize (*"for decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*) was entirely CERN related while the 1999 Nobel prize for 't Hooft and Veltman (*"for elucidating the quantum structure of electroweak interactions in physics"*) made explicit reference to the superb results of CERN's LEP project.

Since 1975 Nikhef, *National Institute for Subatomic Physics*, coordinates the Dutch activities at CERN. Nikhef was a founding member of the general purpose ATLAS experiment, and of the LHCb experiment dedicated to the study of the matter-antimatter differences in systems with beauty (b) quarks. In 1994 Nikhef joined the ALICE experiment, which is optimized to study the quark-gluon plasma. Nikhef has made major contributions often in collaboration with (Dutch) industry, to the construction of all three detectors. Moreover within the context of BiG Grid, *the Dutch e-Science Grid*, the Netherlands created *NL/Tier-1*, one of the 11 world-wide Tier-1 grid centres for LHC data analysis.

In the second half of this decade major upgrades of both the LHC machine and the LHC experiments are envisaged to increase the event rate by an order of magnitude, to further boost the LHC discovery potential. These upgrades are essential to assess the intricacies of the Higgs mechanism (ATLAS); to reach the ultimate precision in specific b-quark systems (LHCb); to maximize the reach for the discovery of new particles (ATLAS); and to allow complementary studies of quarks and gluons under extreme conditions (ALICE). The detector upgrades heavily rely on state-of-the-art silicon strip and –pixel technologies and fast electronics, areas in which Nikhef has an excellent track record. To deal with the data analysis challenges inherent to high-luminosity LHC-operations, the NL/Tier-1 grid facility must be upgraded as well. Whereas the upgrade of the LHC machine proper is funded from the annual contributions of the CERN member-states, the upgrades of the LHC detectors and the (grid) computing facilities must be funded by the experimental collaborations. In this proposal we request in total 18.4 M€ investment funding: 12.4 M€ for the upgrades of the ATLAS, LHCb and ALICE detectors and 6 M€ for the continuation of NL/Tier-1. Dutch (high-tech) industries will be involved in the realization of these upgrades.

The LHC project is a curiosity-driven research activity and attracts as such a huge interest from the general public and from the next generation of scientists. Particle physics has also proven significant societal impact, notably in high-tech areas –one of the nine recently identified research priorities (*'topsectoren'*) of the Dutch government– such as information technology and (medical) diagnostic systems. State-of-the-art pixel detectors originating from LHC detector R&D are now used in commercially available X-ray diffraction systems. The *World Wide Web* (WWW), invented at CERN in the early nineties, partially explains the thriving AMS-IX location at Nikhef. Nikhef's pioneering role in the grid compute concept is one of the reasons why the *European Grid Infrastructure* (EGI) is headquartered at Science Park Amsterdam.

Summary of the research proposal in layman's terms

The LHC is the world's most powerful particle accelerator. The LHC experiments are expected to clarify some of mankind's most intriguing mysteries:

- *What is the Universe made of?*
- *How does the Universe work?*

Anticipated breakthroughs are: elementary-particle masses (*Higgs*); matter-antimatter asymmetry (*CP-violation*); and dark matter (*supersymmetry*).

This proposal requests 18.4 M€ investment funding for the LHC-detector upgrades (including the Dutch grid-compute centre *NL/Tier-1*), thereby securing the present excellent position of Dutch physicists to exploit the LHC discovery potential.

Key words

- Elementary particles
- Particle detectors
- Grid computing
- High technology
- CERN

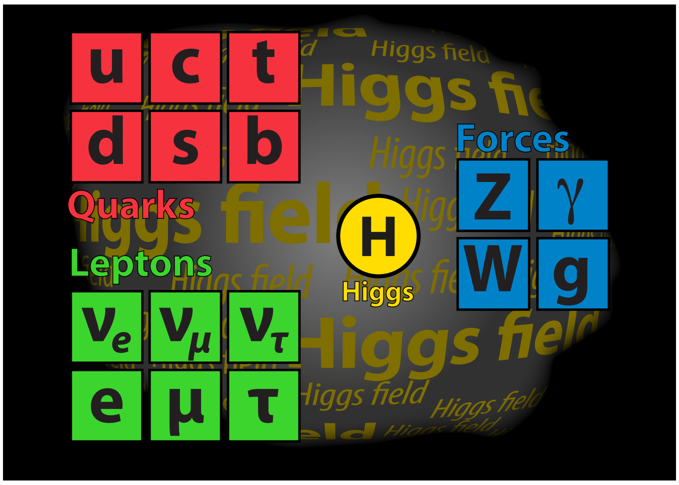

Figure 1. The elementary particles of the Standard Model, including the Higgs particle.

Main field of research

NWO subcommittee (Choose one)

Humanities and Social Sciences	
Natural and Technical Sciences	X
Biomedical and Life Sciences	

NWO Division (Choose one or more)

ALW	
CW	
EW	
GW	
MaGW	
ZonMw	
N	X
STW	

Main field of research

Code: 12.10.00	Field of research: Subatomic physics

Research proposal

Development of the facility in recent years

A1. Assessment of the progress

The LHC

For the accelerator crew it was a three-year marathon at the pace of a sprint, as the accelerators went through the various phases of the first LHC run ('Run-1'). During 2012 —the last full year of operation before the first long shutdown— the accelerator complex pulled off some Olympic performances in terms of increased energy and record luminosity. The year ended with an unprecedented volume of data for the LHC experiments.

In 2012, the LHC started operation with protons in April, with the collision energy increased to 8 TeV from the 2011 level of 7 TeV. Less than two weeks later, the number of bunches per beam reached 1380, the target value for 2012. By June, the LHC had produced more data for the experiments than during the whole of 2011. Thanks to this large data sample, which when added to that from 2011 gave a total of 12 fb^{-1} of integrated luminosity, the experiments were able to identify a new particle consistent with the long-anticipated Higgs particle. Following the announcement of the discovery, CERN decided to extend the proton run by seven weeks. In the end, the total integrated luminosity delivered to the experiments exceeded all predictions, reaching *e.g.* about 25 fb^{-1} for ATLAS alone for Run-1.

In the last week of operation, the teams halved the spacing between bunches from 50 to 25 nanoseconds (ns), with fewer protons per bunch. This set-up is of more interest to the experiments as it reduces the pile-up of events. In parallel, it increases the volume of data accumulated, since the number of bunches is doubled. For the LHC, this mode of operation is delicate because the beams are less stable, particularly because of the electron-cloud phenomenon, which increases as the number of bunches increases. The results of the test were therefore awaited with tension. The teams managed to conduct a physics run with 396 bunches per beam, with 25 ns spacing and at a collision energy of 8 TeV. In the LHC, the compression of the beams at the point of collision was increased, while for the injectors efforts focused on the brightness of the beam, or to put it another way, on the density of particles per unit surface area. Constant optimization made it possible to increase the brightness of the proton bunches by a factor of three. All these efforts are essential for a smooth accelerator operation during Run-2; the next LHC run at full design energy (14 TeV), scheduled to start in 2015.

The LHC computing grid

Essential to the LHC success is the flawless operation of the *Worldwide LHC Computing Grid* (WLCG), a network of state-of-the-art compute centres now totalling 190 PB (1 PB=1,000 TB=1,000,000 MB) of disk space and about 180,000 CPU cores. One of the so-called Tier-1 centres (subject of this proposal) is operated jointly by Nikhef and SURFsara, and was made possible by the high-profile 29 M€ BiG Grid subsidy awarded to Nikhef and partners in 2006 and covering the 2007–2012 period.

The past years BiG Grid attracted a large and diverse scientific community, ranging from particle physics, astronomy, life-sciences and social sciences to the humanities, and offered not only grid services, but also the High Performance Computing (HPC) cloud environment, and the software framework Hadoop for batch processing of very large data-sets. BiG Grid marked its success by a memorable event on 26 September 2012: the *'BiG Grid & beyond'* symposium in the *Beurs van Berlage*, Amsterdam, where both the chairman of NWO and the chairman of SURF underlined the importance of the project's contribution to the national e-infrastructure.

The LHC experiments

Immediately from the start of LHC Run-1 in November 2009, the performance of the different sub-detector systems of the ATLAS experiment has been very good and the overall data collection efficiency is as high as 95%. The large barrel muon chambers (MS) constructed by Nikhef operate well, with a minimal number of defective channels, and also the alignment system and the detector-control system operate as designed. The semiconductor tracker (SCT) operates with high efficiency. Studies of dark current and noise show that the radiation damage to the sensors is understood and follows the prediction well. This gives confidence that, with the necessary maintenance, the detector can be safely operated until 2022, as designed. Nikhef is also involved in trigger and data acquisition systems, which have been operated with trigger- and data rates at or above design values. Nikhef made major contributions to the muon spectrometer reconstruction software.

The Nikhef group contributed to LHCb with unique expertise on all aspects of charged particle detection. This includes leading contributions to detector hardware (the *Vertex Locator*, VELO, and the *Outer Tracker*, OT), to the trigger, and to on- and offline track reconstruction software. The VELO is a silicon-strip detector that operates inside the beam vacuum. The vacuum tank and the vacuum control system were built at Nikhef. To obtain optimal resolution for vertex detection the detectors are positioned at a distance of only 8 mm from the LHC beams. During injection of the LHC beams, the detectors are retracted to a safe position at 3 cm from the beam line. The open/close system, which positions the detector with an accuracy of 5 μm, was also designed and built at Nikhef. Due to the close proximity to the beams, the LHCb experiment has superior vertex resolution compared to the other LHC experiments. To minimize aging of the silicon sensors, they are cooled down to −10 °C, using an innovative binary-phase CO_2 cooling technique developed by Nikhef. This technology is currently being adopted by all other LHC experiments and is considered by ASML, the world's leading manufacturer of lithography equipment.

The Nikhef ALICE group has played a leading role in the design, construction and commissioning of the two outer layers of the *Inner Tracker System* (ITS): the *Silicon Strip Detector* (SSD). The ITS (and notably the SSD) is the most lightweight tracker of its kind and is extremely important for charged particle tracking and essential for the reconstruction of hadrons that contain heavy quarks. Currently we still share the responsibility for the performance of the detector and its electronics. Both (detector and electronics) function extremely well. Our focus on heavy-quark production in heavy-ion collisions nicely matches our past hardware effort in the ITS.

ATLAS	LHCb	ALICE
Commissioning and operation of muon detector and silicon-strip detector, development of muon-track reconstruction software.	Commissioning and operation of the outer tracker and vertex-locator silicon tracker, development of trigger, track reconstruction and alignment software.	Commissioning and operation of the silicon-strip detector.

Table 1. Detector related work of the Nikhef experimental groups in the last years.

Data taking

The different physics goals of the experiments are reflected in the accumulated integrated luminosities (Fig. 2). A common feature of the processes studied by ATLAS is the presence of particles with high transverse energy. These are relatively easy to recognize, also at design luminosity (10 $nb^{-1}s^{-1}$) with many overlapping events[1]. LHCb, on the contrary, relies for many of its analyses, on the complete reconstruction of difficult event topologies involving displaced decay vertices. This can only be achieved in a relatively clean environment with a limited number of overlapping events and therefore the luminosity at the LHCb interaction point was limited to about 0.4 $nb^{-1}s^{-1}$. The stringent requirements on tracking and particle identification for ALICE impose the use of long drift times for some detectors (up to 80 μs), which prohibits operation with only 25 ns between subsequent collisions. Instead only one pair of bunches collides in the ALICE interaction point thereby effectively reducing the luminosity by a factor 1000 compared to ATLAS.

The common feature between the experiments is that each reduces the gigantic data volume via a stepwise real-time event-selection process (*trigger*) to a manageable volume of typically a few hundred events per second corresponding to a few Gb/s. This rate is then distributed to the dedicated grid computing infrastructure of the WLCG for archiving, reconstruction and analysis. The trigger is a crucial ingredient of all LHC experiments since each rejected event is irretrievably lost. Therefore the trigger-logic must take into account Standard Model physics as well as New Physics.

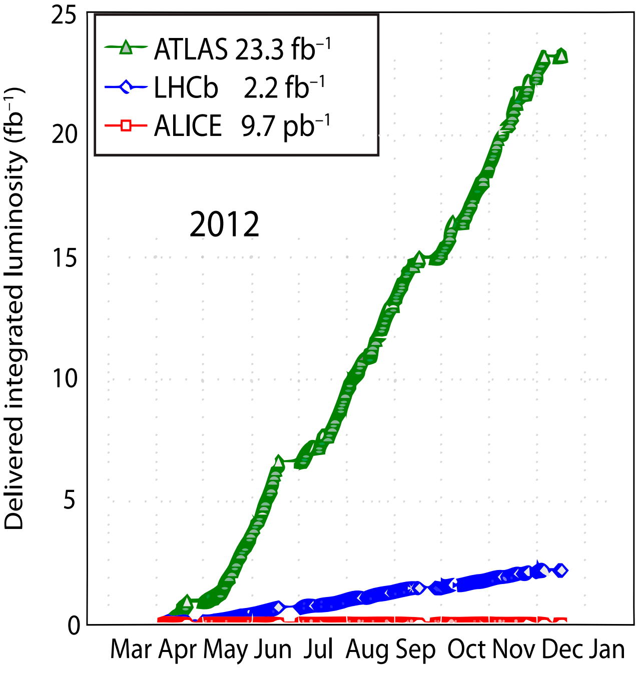

Figure 2. The integrated luminosity of ATLAS, LHCb and ALICE in 2012.

1 At standard LHC design operations, particle bunches collide at a rate of 40 MHz, *i.e.* every 25 ns. With a total proton-proton cross section of 10^8 nb, the average number of interactions (*i.e.* number of overlapping events) at design luminosity (10 $nb^{-1}s^{-1}$) becomes: $10^8[nb]\times 10[nb^{-1}s^{-1}]/40\times 10^6[s^{-1}]=25$. The average of one event per bunch-bunch crossing is reached at a luminosity of 0.4 $nb^{-1}s^{-1}$.

A2. Assessment of the results

ATLAS: A new particle

After the excitement of the first hints of a particle that could be a Higgs particle in 2011, expectations were high as 2012 began. Once LHC data taking at 8 TeV had started in early April, the ATLAS experiment began to record an integrated luminosity of up to 1 fb^{-1} each week. With each run, the data were recorded, calibrated, reconstructed, validated and delivered to the physics analysis teams on a regular basis. At first, the analysis teams searching for Higgs particles restricted their attention to signal-free 'control regions', aiming to prove to themselves and their colleagues that the new data were thoroughly understood. After a series of review meetings, with just a few weeks remaining before the main conference in the field (ICHEP, Melbourne, July 2012), the go-ahead was given to 'un-blind' the data taken up to that point. This was a moment of great excitement tinged with anxiety.

Figure 3. Peter Higgs (left) and Stan Bentvelsen (former Nikhef-ATLAS programme leader; right) after prof. Higgs' colloquium at Nikhef.

The signal of something new with a mass around 125–126 GeV became increasingly visible as more data were added week-by-week and combined with the results from improved analyses of the 2011 data. It rapidly became clear that there was a significant signal for the decay of a new particle both to two photons and to four leptons. The last two weeks before the announcement were particularly intense, with exhaustive crosschecks of the results and many discussions on exactly how to present and interpret what had been seen. With the inclusion of nearly 6 fb^{-1} of data at 8 TeV, ATLAS had signals with significances of 4.5 standard deviations (or sigma, σ) in the two-photon channel and 3.4 σ in the four-lepton channel. This allowed the ATLAS collaboration to report the observation of a new particle, together with the CMS collaboration, at the special seminar held at CERN and broadcast to the world on 4 July. At last it was clear: a new particle had been discovered and the decays to two photons proved that it had to be a particle with integer spin (a boson). By the end of the year, the ATLAS signal-significance had risen to above 10 sigma.

While these results established beyond doubt the existence of a new particle, its exact identity remained uncertain. New techniques were developed to reveal its identity by measuring its spin and parity —properties of particles that relate to their angular momentum and their mirror image. ATLAS has found that the new particle is much more likely to have zero spin and positive parity than other values. These are interesting results and necessary, though not sufficient, to claim that it is the Standard Model Higgs particle.

ATLAS: Looking for surprises

Sophisticated and creative techniques have been developed to search for further new particles. One example relates to the search for dark matter —invisible matter that seems to account for 26% of the content of the Universe (ordinary matter made of quarks and leptons, see Fig. 1, amounts to only 5%). One way to find out if this mysterious form of matter is produced in collisions at the LHC is to search for 'unbalanced' events, in which a number of high-energy jets or particles are produced recoiling against a pair of undetected particles that could be dark matter (since dark matter would be invisible to the detectors). Limits can then be set on how often weakly interacting massive particles (WIMPs) —hypothetical particles that could form dark matter— would interact with ordinary matter. A highlight in 2012 for the ATLAS collaboration was to use the full 2011 dataset to set limits for WIMPs that are complementary to limits set by experiments looking for direct detection of dark matter.

One promising idea that goes beyond the Standard Model and that could provide an explanation for dark matter is supersymmetry (SUSY) —a new symmetry in Nature that requires that all particles have heavier 'superpartners'. ATLAS has performed searches for many different types of supersymmetric particles, including those that are the supersymmetric partners of the top and beauty quark, and of the photon, W, Z and Higgs boson, as they could be relatively light. Just as with dark matter, many of these searches involve finding events in which weakly interacting particles escape the detectors unseen. This makes it essential to have detectors that are hermetic, fully operational and well understood, since even a slight malfunction could mimic a 'missing' particle. The ATLAS detector fulfilled these requirements, despite the challenge imposed by high 'pile-up', where on average 25 other collisions take place at the same time as the collision of interest.

LHCb: Beauty and charm

Specializing in particles with lower masses, the LHCb experiment focuses on precision measurements of particles containing beauty (b) quarks, such as B mesons, as well as those having lighter charm (c) quarks, the D mesons. Thanks to smooth operation, data corresponding to an integrated luminosity of 3.1 fb^{-1} was collected over the years 2011 and 2012 with a fully operational detector. In these two years, LHCb has overtaken the competition, 'B factories' —electron–positron colliders tuned to produce pairs of B particles and their antiparticles— as the leading facility for measurements related to matter–antimatter differences.

The observation that decays of B^0_s mesons (particles composed of a beauty antiquark and a strange quark) exhibit large matter-antimatter asymmetries opened a new field of research in which stringent tests of Standard Model predictions can be performed. Furthermore, the existence of matter to antimatter transitions for neutral D mesons was established, such that these so-called flavour oscillations have now been found to occur for all types of neutrally charged heavy-quark mesons: strange, charm as well as beauty.

This wealth of data allowed LHCb to find the first evidence for the disintegration of a B^0_s into two muons, $B^0_s \rightarrow \mu^+\mu^-$. With only three or four such events occurring for every 1000 million B^0_s decays, this is one of the rarest decays ever seen. The number of events observed by LHCb agrees with predictions from the Standard Model, albeit with a large statistical uncertainty. The collaboration also obtained the world's most stringent limit for the decay of the B^0_d (composed of a beauty antiquark and a down quark) to two muons. Taken together, these two results had a huge impact on various SUSY models, helping to guide theorists in the right direction.

ALICE: Hot matter

Quark–gluon plasma (QGP) is a state of matter that probably existed just after (much less than a millisecond) the Big Bang, when the temperature was much too high for quarks to 'condense' into protons and neutrons, the building blocks of today's matter. At the LHC, the head-on collisions of lead ions —lead atoms fully stripped of electrons— allow the study of such hot, dense matter; a specialty of the ALICE experiment.

As the QGP cools down during the rapid expansion of the initial 'fireball' created in heavy-ion collisions, quarks become trapped to form hadrons (ordinary matter), which can then be detected. Measuring the global pattern of the emission of these hadrons, as well as their detailed composition, ultimately sheds light on the properties of the QGP. Using the spectrum of photons escaping from the fireball created in collisions, the ALICE collaboration estimated the effective temperature reached in the lead–lead collisions at the LHC. The result, a value of 1.8×10^{12} kelvin (K), is a million times higher than the temperature in the core of the Sun and high enough to form QGP. This is the highest temperature ever observed in a laboratory.

September saw the LHC's only operation with lead ions in 2012, in a first test of collisions between protons and lead ions. Lead ions contain 208 protons and neutrons, so to improve the understanding of what happens when these composite objects collide, the collaboration decided to study proton–lead collisions. This should help to disentangle effects that come from free protons, from effects associated with the many-body medium created in heavy-ion collisions. Data on proton–proton collisions already provide an important part of this disentanglement effort. By looking at the density of charged particles produced in the collisions, ALICE was able to discriminate between theoretical models and to determine which ones adequately describe the initial state of the lead ions.

An unexpected and still unexplained phenomenon originally observed in heavy-ion experiments at other laboratories concerns the 'ridge' effect —a clustering in space of pairs of particles produced with different momenta. This effect was observed at the LHC in proton–proton data in 2010, then in lead–lead data in 2011, and most recently in the proton–lead data, where the effect seems as strong as in the lead–lead data. An even more recent surprising effect was the measured double-ridge structure. These results raise the question: *Can a QGP-like matter be formed in simple proton–lead collisions?*

Future development of the facility

B1.1 Science case

The past century: the Standard Model of elementary particles

Throughout the 20th century immense progress has been made in unravelling and understanding the structure of elementary particles and fields: from the chemical elements to three families of quarks and leptons and their antiparticles; from the classical theory of electromagnetism to relativistic quantum field theories culminating in the Standard Model of the electroweak and strong interaction. Throughout, accelerator-based experiments have played a decisive role as witnessed *e.g.* by: Thomson's discovery of the electron (1897) using cathode rays; the discovery of the W and Z-bosons (1983) at the CERN Sp$\bar{p}$S; the discovery of the top-quark (1995) and the τ-neutrino (2000) at the Fermi Laboratory's Tevatron; and the recent discovery of the Higgs particle (2012) at CERN's Large Hadron Collider. Until its discovery, this Higgs particle had been for a very long time the only critical ingredient of the Standard Model lacking experimental verification. The Standard Model not only very successfully describes a plethora of high-precision data from particle-physics experiments all around the world, but also allows a qualitative and quantitative description of the evolution of our Universe, from a minute fraction of a second after the Big Bang to today, about 13.8 billion years later. Thereby, the Standard Model links apparently completely unrelated observations like the disappearance of antimatter, the abundance of the natural elements in our Universe as observed by astronomers, and the number of particle families (*i.e.* the number of light neutrino species) as measured in particle accelerator experiments. The Standard Model also connects the science of the infinitely large (astronomy) to the science of the infinitesimally small (particle physics).

The future: beyond the Standard Model of elementary particles

Nevertheless, despite the many and astonishing successes and high-precision of the Standard Model, experiments, observations and theoretical speculations have revealed a Universe far stranger and even more wonderful than predicted by the Standard Model. A Universe, filled with dark matter and dark energy, where ordinary matter (quarks and leptons) constitutes only a tiny 5% fraction. A Universe, in which theorists predict each Standard-Model particle to be accompanied by a supersymmetric partner. A Universe, in which theorists, in their attempts to reconcile the theory of gravitation with the principles of quantum mechanics, predict the existence of curled up extra spatial dimensions invisible in our everyday world. A Universe, in which neutrinos oscillate, *i.e.* change flavour. And perhaps less revolutionary, even within the context of the Standard Model, several issues require further experimental clarification. Does the recently discovered Higgs particle indeed couple to the matter particles (the quarks and leptons) as predicted by the Standard Model, *i.e.* proportional to their masses such that we might start to understand the origin of mass? Are the Higgs couplings to the massive W- and Z-bosons in accord with the mechanism of electroweak symmetry breaking as implemented in the Standard Model? Are the Higgs quantum numbers (notably spin and parity) in agreement with the Standard Model? Furthermore, even though the Standard Model incorporates a description of minute differences between matter and antimatter, this description falls many orders of magnitude short to describe the evolution from a balanced matter-antimatter Universe at the time of the Big Bang to today's Universe void of antimatter. Also, the Standard Model predicts the existence of a new state of matter at high temperature and density in which quarks and gluons are no longer confined inside hadrons like protons and neutrons: the quark-gluon plasma. This quark-gluon plasma supposedly played an important role in the very early Universe and requires further investigation. Despite the often impressive theoretical ingenuity of many models and despite the quantitative accuracy of some of the predictions, we know experimentally amazingly little about Nature at its most elementary level. We still speculate about the properties of Higgs particle(s), neutrinos, matter-antimatter asymmetries, and on the existence of supersymmetric particles, the quark-gluon plasma, dark matter, dark energy and extra spatial dimensions.

The next step: LHC

CERN's LHC project is expected to yield the experimental evidence needed to answer (some of) the above mentioned fundamental questions in the coming years. A validation of any of the above speculations or the discovery of something entirely unexpected, will certainly revolutionize our view of the Universe. This is why the expectations of the LHC surpass those of any other (present and past) accelerator project. It is also understood that any future accelerator project at the energy frontier will only be decided upon once the LHC has thoroughly explored the TeV scale.

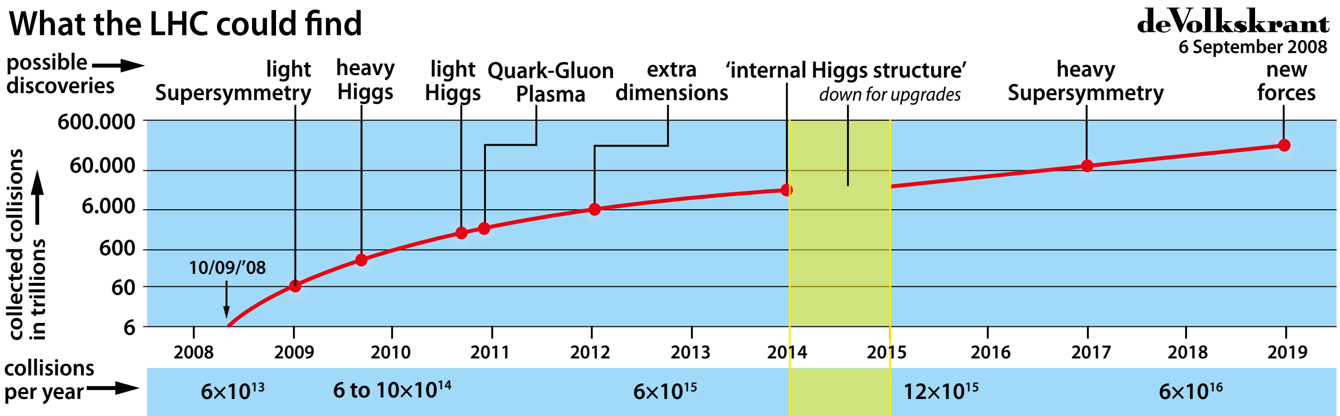

Figure 4. An at that time (2008) optimistic (timewise, not topic-wise) overview of possible LHC discoveries by Martijn van Calmthout, the science editor of the Volkskrant, a national newspaper. In fact, the LHC experiments were delayed by more than a year due to a beam incident on 19 September 2008. A light Higgs particle was discovered in 2012; 1.5 years later than indicated in the figure.

LHC running schedule

In the first years of LHC running, 2010-2011, the beam energy was limited to 3.5 TeV. In 2012 the beam energy was increased to 4 TeV. Simultaneously, the number of colliding particle bunches and the intensity per bunch (and hence the luminosity) was gradually increased. Presently, a long period (2013-2014) of work on the accelerator and the detectors is underway. For the experiments this stop means that sub-detectors can be repaired, improved or even extended. For the accelerator it means, apart from repairs and maintenance, the completion of the safety precautions to allow safe operation of the LHC bending magnets at full magnetic field strength. After the necessary checks and repairs the LHC beams are foreseen to attain the original design energy of 7 TeV per beam and design luminosity of 10 $nb^{-1}s^{-1}$ in 2015. Further shutdowns are foreseen for 2018 and 2022–2023. In these shutdowns the experiments plan major upgrades, in particular of their tracking detectors, to cope with the higher particle fluxes (*i.e.* higher radiation loads) inherent to the luminosity increase of the accelerator and/or to take advantage of the availability of new detector and computing/electronics technology to further boost their discovery potential. After the last (2022–2023) shutdown the LHC should run for about a decade to deliver at least 3000 fb^{-1}; *i.e.* a tenfold increase compared to the anticipated accumulated data set in the prior years. This vast data sample is required to *e.g.* map out the intricacies of the Higgs sector such as the extremely rare $H \rightarrow \mu\mu$ decay and to assess the Higgs potential which is at the heart of the mechanism by which the particles in the Standard Model acquire their mass. At the same time this large data sample will extend the mass range for the discovery of new particles by about 30%[1]. At that moment, after more than 20 years of LHC operation, the future of the LHC will depend on where we stand and in particular: *Do we understand the mechanism of symmetry breaking in the Standard Model?*, and *Did we discover physics beyond the Standard Model?* If required, a doubling of the LHC beam energy by replacing all LHC bending magnets by more powerful ones is considered. The research on such magnets has already started.

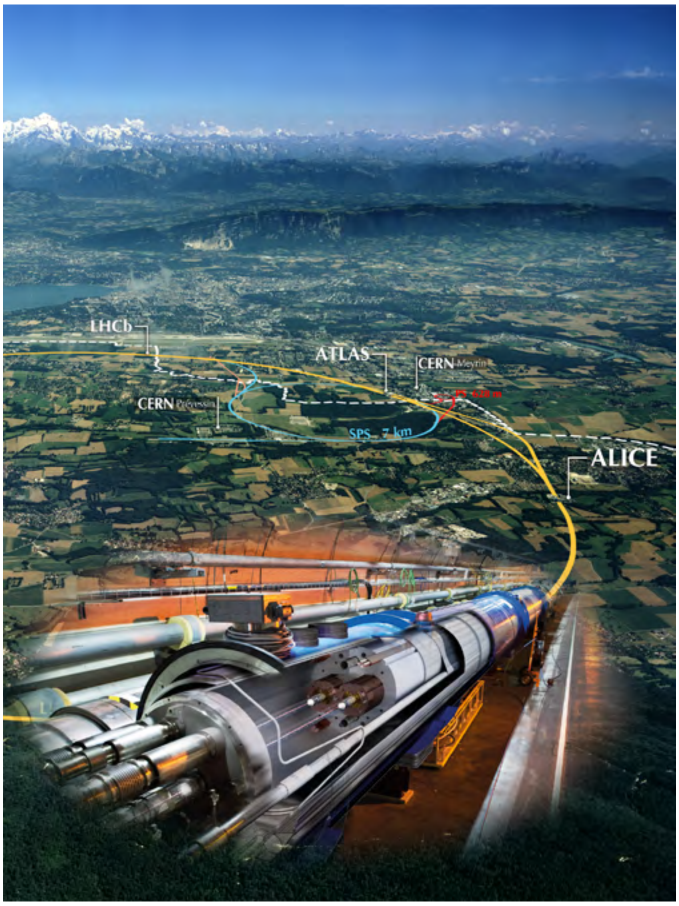

Figure 5. The Large Hadron Collider.

The Worldwide LHC Computing Grid (WLCG)

The *Worldwide LHC Computing Grid* was launched in 2002 to provide global computing resources to store,

1 At proton-proton colliders the fundamental interaction is between the proton constituents, *i.e.* the quarks and gluons. These constituents only carry a fraction of the proton-beam energy and therefore the centre-of-mass energy of the fundamental interaction at LHC ranges from zero to the maximum achievable value of twice the proton-beam energy. The latter only occurs extremely rarely and it is by increasing the integrated data sample (*i.e.* the integrated luminosity) that one gets access to the energetic fundamental interactions and thereby possibly new particles with large mass.

	LHC machine	LHC experiments
Run-1 2010–2012	7-8 TeV c.m. energy, luminosity ramping to few $nb^{-1}s^{-1}$	30 fb^{-1} delivered
2013–2014	LHC consolidation: Prepare machine for design *i.e.* 14 TeV centre-of-mass energy and nominal luminosity	ATLAS: inner pixel detector layer LHCb: consolidation ALICE: detector completion
Run-2 2015–2017	14 TeV c.m. energy, luminosity ramping to 10 $nb^{-1}s^{-1}$	expect to collect 50–100 fb^{-1}
2018	LHC phase-1 upgrade: Injector complex upgrade to ultimate luminosity	ATLAS: muon chambers, trigger, data-acquisition (Phase-I) LHCb: trigger upgrade, vertex detector ALICE: inner tracking system, TPC, data-acquisition
Run-3 2019–2021	14 TeV c.m. energy, luminosity ramping to 2.2×nominal	expect to collect 300–400 fb^{-1}
2022–2023	LHC phase-2 upgrade (High-Luminosity LHC): New focussing magnets and CRAB cavities for very high luminosity with luminosity levelling at 50 $nb^{-1}s^{-1}$	ATLAS: inner tracker, data-acquisition (Phase-II) ALICE: forward detectors
Run-4 2024– …	14 TeV c.m. energy, High-Luminosity LHC	collect data until at least 3000 fb^{-1}

Table 2. Provisional LHC schedule.

distribute and analyse the estimated 15 PB (*i.e.* 15 million GB) of data annually generated by the four LHC experiments together. The WLCG interconnects thousands of computers and storage (disk and tape) systems at hundreds of data centres all across the world in a hierarchical manner on a scale never realized before. At the top is the so-called Tier-0 centre which receives raw data at rates of typically a few Gb/s directly from each LHC experiment. The Tier-0 sends a copy of the raw data (for backup and analysis) to one of the 11 so-called Tier-1 centres located in Europe (7), America (3) and Asia (1). A high-speed optical network (tens of Gb/s) interconnects the Tier-0 and Tier-1 centres. Smaller Tier-2 and Tier-3 centres are connected to the Tier-1 centres. Registered users can access the WLCG resources in a transparent manner directly from their desktop and thereby submit analysis jobs to be executed somewhere on the WLCG and using data samples stored anywhere on the WLCG.

To convert the just-described WLCG-concept into a smoothly functioning facility serving a worldwide community of more than 8,000 physicists with near real-time access to LHC data, and the power to process these data (even while each of the four LHC experiments injects a few Gb/s of raw data into the system), turned out to be a herculean task. It was only achieved thanks to the collaborative efforts of hundreds of people throughout the world and after a set of so-called data challenges spread over a few year period. Each successive data challenge tested ever more strenuous facets of the real LHC compute and data storage/retrieval requirements. Since 2009 the WLCG functions perfectly as is best demonstrated by the fact that all four experiments are able to convert raw data into physics results at a remarkably fast pace, sometimes even within weeks.

The LHC experiments

Fig. 6 shows proton-proton collision cross sections and the corresponding event rates for some representative processes at the luminosity (L) of 1 $nb^{-1}s^{-1}$ to illustrate that the LHC will produce large numbers of $b\bar{b}$- and $t\bar{t}$ quark pairs, W- and Z particles and even Higgs particles.

To keep full advantage of the already scheduled LHC machine improvements, the LHC experiments must upgrade their detector systems and data-acquisition

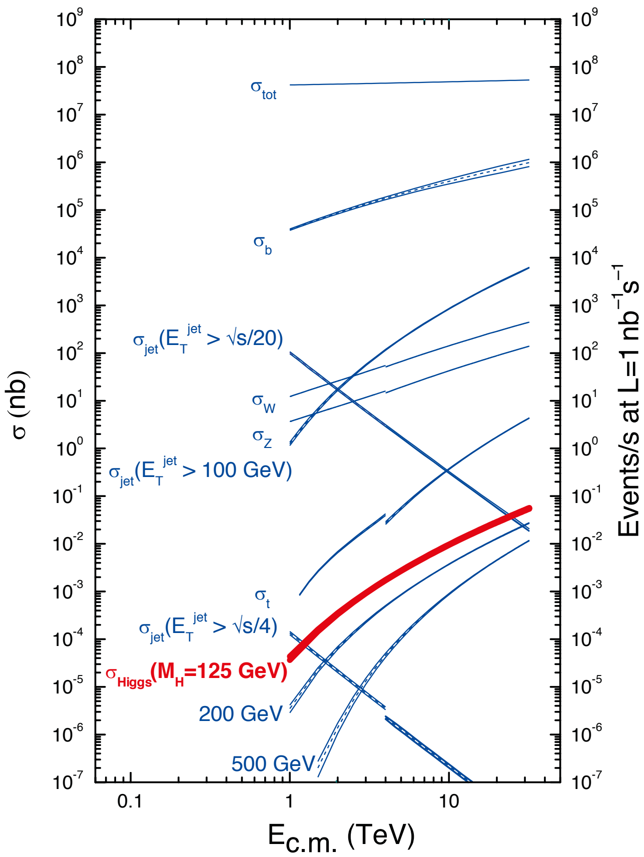

Figure 6. Representative proton-proton cross sections versus the centre-of-mass energy.

electronics. Also the steadily increasing data volumes demand a matching expansion of the WLCG capacity. Without these upgrades the experiments will be unable to keep up with the planned peak luminosity increases (about an order of magnitude compared to today's peak luminosity). This would be detrimental because many measurements (*e.g.* detailed Higgs studies, searches for rare B-decays and high-mass particles) rely on large data samples, which otherwise would require a century of LHC operation at today's running conditions to accumulate! With these upgrades, the LHC discovery potential will be exploited timely and efficiently. More details hereof are presented in Section B6 *technical case*.

ATLAS

The ATLAS collaboration was established in 1991 with Nikhef as a founding member, and consists of about 3,000 physicists (including 1,000 PhD students), coming from 174 institutes in 38 countries. Over a time span of almost two decades the collaboration designed, built and commissioned the world's largest particle detector, 25 meters high, 44 meters long, with a weight of 7,000 tons, and with 90 million electronic channels. The Nikhef ATLAS group consists of physicists of the Radboud University Nijmegen, University of Amsterdam and FOM.

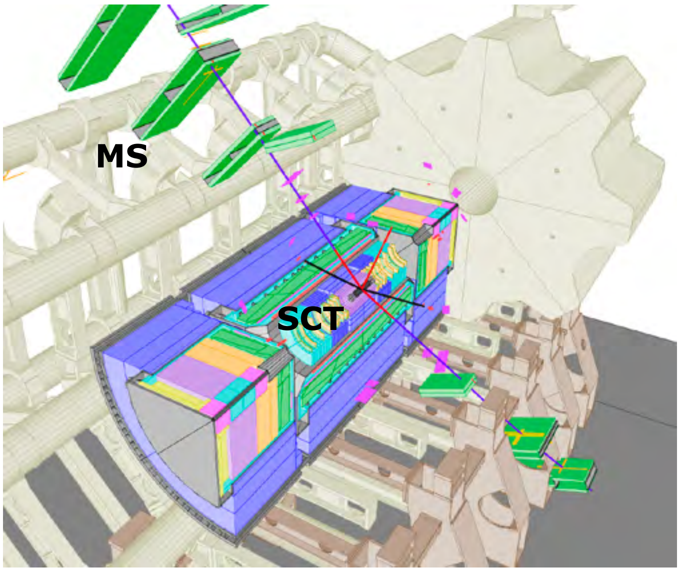

Figure 7. ATLAS detector with tracks of the decay of a Higgs particle in 2 electrons and 2 muons. The Muon Spectrometer (MS) and SemiConductor Tracker (SCT) are indicated.

As a general-purpose experiment, ATLAS has a rich physics program. The main goals are:

- To clarify the mechanism of electroweak symmetry breaking. Within the Standard Model, the electroweak symmetry breaking proceeds through the mechanism described by Higgs, Brout and Englert, leading to the prediction of the existence of a new scalar particle, the Higgs particle. Before the LHC started operations, this theory lacked experimental verification. In 2012 ATLAS (together with CMS[1]) discovered a new particle consistent with the Higgs. The further clarification of electroweak symmetry breaking involves a study of the exact nature of this new particle, in particular a measurement of its couplings to the other Standard Model particles and to itself, to investigate whether the new particle behaves like the Standard Model Higgs particle, or whether New Physics is at play;
- To test the Standard Model at the highest available energies. The high collision energy and luminosity provide opportunities to measure Standard Model processes to a precision and under circumstances never reached before;
- To search for new particles at the TeV scale. Even after the discovery of the Higgs particle, a number of essential questions remain that cannot be answered within the Standard Model. Many speculative theories beyond the Standard Model, like supersymmetry and models with extra dimensions, propose solutions to these questions, by predicting the existence of new particles with masses of around a TeV. The LHC reaches this mass range and ATLAS will sweep over a large number of scenarios searching for these particles;
- To produce and identify the particles that make up the dark matter in the Universe. The most plausible explanation for the large fraction of the mysterious dark matter in the Universe is the existence of a hitherto unknown, stable, electrically-neutral particle. Indeed, a number of speculative theories predict stable neutral particles that could be identified as dark matter, thereby eventually solving its mystery. ATLAS is very well suited to discover and study such particles, in particular (but not only) in the context of supersymmetry.

In 'Run-1' (2010-2012), ATLAS collected 5 fb^{-1} and 20 fb^{-1} at centre-of-mass energies of 7 TeV and 8 TeV, respectively. To date, ATLAS published over 270 scientific papers and approximately 530 conference contributions, on topics ranging from the discovery of the Higgs particle, precision measurements of top quark, W and Z production, tests of quantumchromodynamics, beauty-quark physics, to searches for physics beyond the Standard Model. For Run-1, the Nikhef ATLAS group has concentrated its efforts on three physics analysis themes: top-quark physics; Higgs physics; and searches for phenomena beyond the Standard Model, in particular supersymmetry. We played a major role in the discovery of the Higgs particle in the WW and ZZ channels, and in searches for supersymmetry.

1 As general purpose experiments, ATLAS and CMS have very similar physics programmes. The Netherlands decided early on to focus its efforts on a single LHC general purpose experiment: ATLAS.

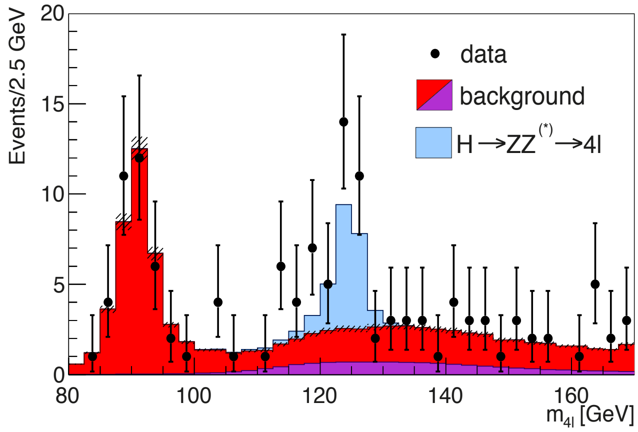

Figure 8. Invariant mass of 4 leptons in the Run-1 ATLAS data, exhibiting a peak that indicates the mass of the Higgs particle around 126 GeV. With the data of the high-luminosity LHC, the number of Higgs particles will increase by a factor 300.

The goal of Run-2 (2015-2017) is to collect 50-100 fb^{-1} at a centre-of-mass energy of at least 13 TeV and hopefully even at the ultimate LHC design energy of 14 TeV. For Run-2, the Nikhef ATLAS group will focus on measurements of properties of the newly discovered Higgs particle and searches for phenomena beyond the Standard Model, like additional Higgs particles and supersymmetry.

To indisputably establish the properties of the Higgs particle, a much larger data sample is needed. Therefore, the peak LHC luminosity will, in a first step, be increased to 22 $nb^{-1}s^{-1}$ (about twice nominal) to accumulate 300–400 fb^{-1} by 2022 (Run-3). After a long shutdown, High Luminosity LHC (HL-LHC) operations should start in 2024 with a levelled (constant) instantaneous luminosity of 50 $nb^{-1}s^{-1}$ with the aim to accumulate 3000 fb^{-1} over a ten year period (Run-4). This large data sample will allow significant improvements in the determination of Higgs couplings, reaching accuracies ranging from 5% to 30% in many channels. In addition also extremely rare channels will become accessible: $H \to \mu\mu$; Higgs production via WW fusion with subsequent $H \to \gamma\gamma$ or $H \to \tau\tau$ decay; and Higgs production in association with a top-quark pair. The large data sample will also allow for the first time to study the Higgs self-coupling and to study high-energy WW scattering; both processes are important tests of the Higgs mechanism of electroweak symmetry breaking. Finally the 3000 fb^{-1} data sample allows to probe the signatures of New Physics, as predicted by models such as supersymmetry and extra dimensions, well into the multi-TeV region.

The harsh (radiation) environment of the HL-LHC poses significant challenges to the ATLAS detector. At the same time, the physics analyses require ATLAS to maintain excellent lepton and jet momentum resolutions up to very high momenta; to retain good capabilities to trigger on and reconstruct low p_T leptons; to identify tau leptons and heavy-flavour decays in events with very high track densities; and to reconstruct leptons and heavy flavours in highly boosted event topologies. To achieve this, major upgrades of several subsystems of the ATLAS detector are envisaged, as detailed in section B6 *technical case*.

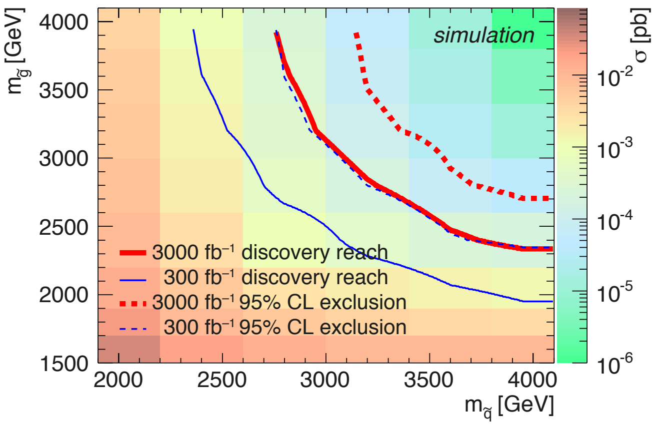

Figure 9. Sensitivity of ATLAS at the HL-LHC for searches for supersymmetric quarks (horizontal axis) and gluons (vertical axis). Particles with masses to the left and below the curves can be either discovered with 5 sigma certainty (full curves), or excluded at 95% confidence level (dashed curves).

LHCb

The LHCb collaboration was established in 1994 with Nikhef as a founding member; presently Nikhef is one of the five largest groups within LHCb. The LHCb collaboration consists of about 620 physicists, representing 63 different universities and laboratories (including five associated institutions) from 17 countries with support of about 250 technicians and engineers. The 4,500 tonne LHCb detector is designed to record the decays of particles containing b-quarks. Since these particles have relatively low mass in comparison to the LHC collision energy, they are produced predominantly at small angles with respect to the LHC beam line. The design of the detector reflects this; instead of surrounding the entire collision point, like ATLAS and ALICE, LHCb is a spectrometer of sub-detectors stretching for 20 metres along the beamline. The Nikhef LHCb group consists of physicists of the VU University Amsterdam, University of Groningen and FOM.

The goal of the LHCb experiment is to search for effects of new particles or forces beyond the Standard Model, generally referred to as New Physics. Complementary to the method of direct production of such new heavy particles, LHCb searches for their virtual quantum effects via precision measurements on decays of particles that contain b- and c-quarks. Historically, studies of hadronic flavour physics observables have provided critical input in the construction of the Standard Model. Flavour measurements provided the first evidence of the existence and nature of the c-quark, the existence of the third generation, and the high mass scale of the t-quark. The LHCb flavour physics programme focuses on two main themes:

- To search for matter–antimatter asymmetries that cannot be explained within the Standard Model. In the Standard Model the Higgs field not only generates masses of the fundamental particles but also simultaneously allows matter and antimatter particles to interact differently via the weak force. This so-called Charge-Parity (CP)-violation phenomenon has its origin in a single free parameter in the Standard Model, but fails to explain the cosmic matter-antimatter asymmetry by many orders of magnitude. LHCb explores the rich structure of decays of particles with b- or c-quarks to subject the Standard Model to a stringent consistency test;

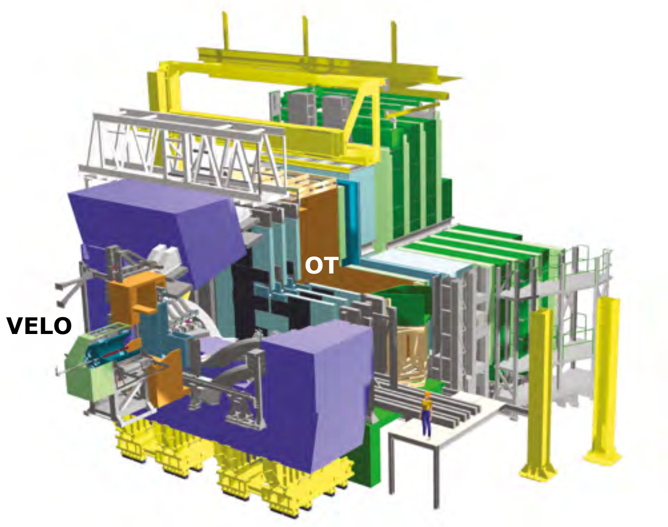

Figure 10. The LHCb detector. The Vertex Locator (VELO) and Outer Tracker (OT) are indicated.

- To search for rare, or even forbidden, decays that are incompatible with Standard Model predictions. The strict rules of the Standard Model forbid couplings of two different quarks or charged leptons to neutral force carriers. Such processes can only occur in higher order quantum loop diagrams, and as such are sensitive to virtual contributions from not yet discovered particles, pointing to New Physics.

Using the LHC as the world's most prolific source of heavy-flavoured particles, the LHCb collaboration has in Run-1 for the first time observed CP-violation in measurements of B^0_s-meson decays, performed a precision measurement of B^0_s–$\bar{B}^0_s$ oscillations (Fig. 11) and detected the hitherto unseen decay of $B^0_s \to \mu^+\mu^-$ (Fig. 12). In Run-2 the hunt for New Physics proceeds by turning the discoveries of Run-1 into precision measurements (Fig. 12), while at the same time searching for even stronger suppressed decay modes.

The physics programme of the Nikhef group is presently focused on B^0_s meson decays into charged particle final states. In various New Physics models the $b \to s$ quark transition is considered to be the most sensitive flavour probe to New Physics. This promising field will remain at the centre of our activity. More specifically, our programme includes the measurements of the properties of the very rare decays $B^0_s \to \mu^+\mu^-$ and $B^0_d \to \mu^+\mu^-$, as well as the determinations of CP-violating parameters to test the validity of the Standard Model.

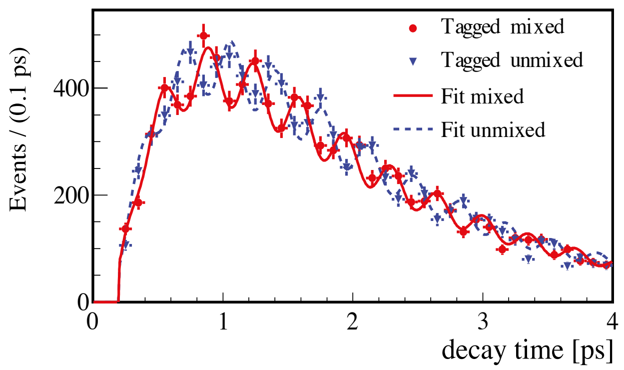

Figure 11. The decay-time dependent B^0_s to $\bar{B}^0_s$ oscillations measurement. The red data and model are due to decays of B^0_s mesons that oscillated, while the blue data and model are due to decays that did not oscillate.

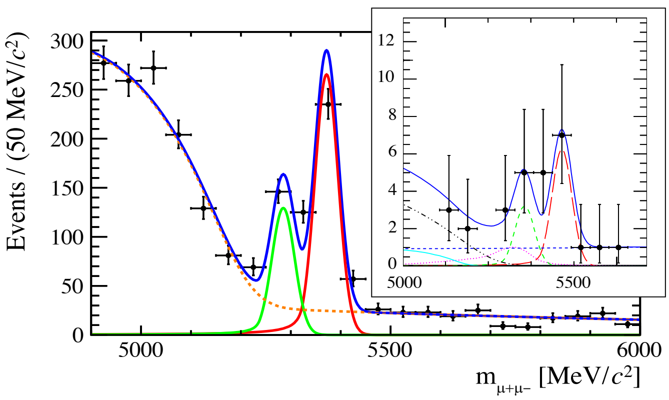

Figure 12. Simulation visualizing the $B^0_d \to \mu^+\mu^-$ (green) and $B^0_s \to \mu^+\mu^-$ (red) signals expected after collecting 50 fb^{-1} of data with the LHCb upgrade. Inset: Real data signal as observed with the current LHCb detector (3 fb^{-1}). The ratio of the $B^0_d \to \mu^+\mu^-$ over $B^0_s \to \mu^+\mu^-$ decay rate will provide a strong constraint for New Physics models.

A new, promising frontier to hunt for New Physics is that of rare decays resulting from flavour violating phenomena in the lepton sector. New Physics models predict the existence of flavour-violating charged lepton decays, but such decays are yet to be observed. If neutrinos are Majorana particles, so-called see-saw mechanisms can generate a lepton-antilepton asymmetry (leptogenesis), which can be transferred to quarks (baryogenesis) via the electroweak phase transition. The Nikhef group plans to extend its physics programme to include two specific lepton flavour topics: the search for heavy Majorana neutrinos and lepton-flavour-violating decays.

ALICE

The ALICE collaboration was established in 1992 and Nikhef joined in 1994. Currently ALICE consists of about 1,200 physicists (including about 200 PhD students), engineers and technicians from 132 institutes in 36 countries around the world. The Nikhef group belongs to the ten largest groups within ALICE. The main aim of the collaboration is to study a new state of matter –the Quark-Gluon Plasma (QGP)– where quark and gluon degrees of freedom are not anymore confined inside hadrons. The QGP is studied using collisions of heavy nuclei, mainly lead on lead (Pb+Pb), with the ALICE detector at the top energy of the LHC. The ALICE detector stands 16 meters tall, 16 meters meters wide and 26 meters long, and weighs approximately 10,000 tons. The Nikhef ALICE group consists of physicists from Utrecht University and FOM.

Within the broad physics program of ALICE, the Nikhef group focusses on:

- The study of the angular correlations between the particles produced in heavy-ion collisions; and
- The clarification of the mechanism of the interactions of the QGP with so-called hard probes.

Perhaps the largest scientific challenge in heavy-ion physics is that it deals with non-perturbative strong-interaction phenomena so that observations usually cannot be confronted with ab initio calculations based on first principles. Instead, a wide variety of models are used to relate the measurements to the properties of the medium created in the collisions. This makes heavy-ion physics a very challenging and rich multidisciplinary field based on perturbative QCD, lattice QCD, particle physics, nuclear physics, string theory (via the AdS/CFT correspondence), thermodynamics and relativistic hydrodynamics.

As in the early Universe, the QGP created in a heavy-ion collision will expand and cool down. This collective expansion (so-called flow) is driven by the pressure gradients. The measurement of flow provides information on the equation of state and on the transport properties of the QGP. The anisotropic flow measurements probably had the highest impact in the last decade. Already in experiments at Brookhaven's *Relativistic Heavy Ion Collider* (RHIC), it was found that the medium created in heavy-ion collisions behaves –unexpectedly– as an almost perfect liquid. This result attracted considerable interest and was selected by the American Institute of Physics as the top physics discovery of 2005. Members of the Nikhef group have played a major role in this analysis. Subsequently, the Nikhef group developed the flow analysis software for ALICE leading to one of the first publications on LHC lead-lead collisions, which, currently is still the most frequently cited ALICE physics paper.

Flow is a genuine multi-particle correlation and for this reason, sophisticated statistical analysis techniques are developed to isolate genuine all-particle correlations from the few-particle correlations that are also abundantly present in the events. A multi-particle correlation analysis is a highly specialized subject and the Nikhef group is in close contact with other experts in the field to further develop these techniques and to implement these in the ALICE software. Further measurements at the LHC aim to differentiate flow in terms of particle species and kinematic variables, while a study of the higher harmonics will give access to the viscosity over entropy ratio, and will further challenge the hydrodynamic paradigm. The QGP can also be studied via its interaction with

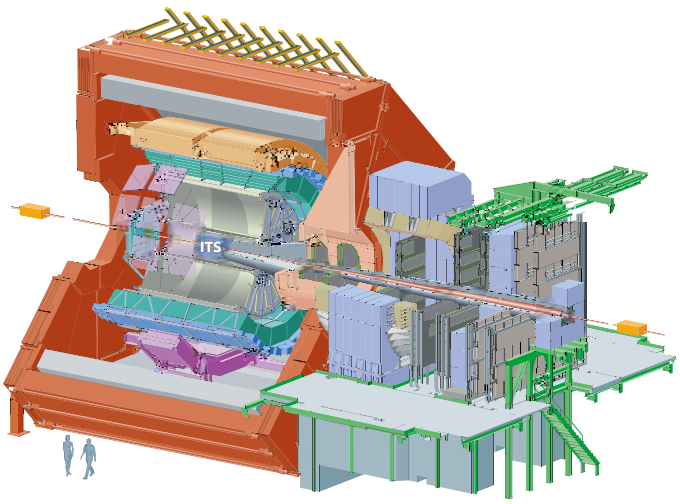

Figure 13. The ALICE detector. The Inner Tracking System (ITS) is indicated.

highly energetic quarks and gluons that are produced in hard scatterings in the early stage of the collision. These highly energetic partons ('hard probes') manifest themselves as hadronic jets or as hadrons containing heavy (c and b) quarks. The Nikhef group is involved in the ALICE studies of jet and heavy-quark production. Hard partons will lose energy when traversing the QGP medium leading to a suppression of jet-production in heavy-ion collisions with respect to that in proton-proton collisions (jet quenching). The goal of jet quenching measurements is first to verify our theoretical understanding of the energy loss mechanism to subsequently use the quenching as a tool to probe the colour-charge density and, via path length dependence, the geometry of the medium. Jets are difficult to identify in the crowded environment of an heavy-ion collision and it is only at the LHC that they sufficiently stand out to be identified reliably.

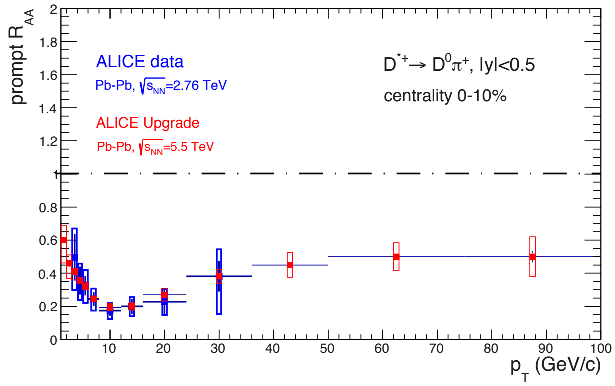

Figure 14. The nuclear modification factor R_{AA} of the D^{*+} meson as function of transverse momentum. At high and low momenta R_{AA} is expected to go up from the minimum value seen at about 10 GeV/c. The current data sample does not allow conclusions on this effect due to the limited reach in transverse momentum (blue points). After the upgrade R_{AA} can be measured from transverse momenta as low as 1 GeV/c up to 100 GeV/c (simulated red points).

The involvement of the Nikhef group in the analysis of heavy-quark production naturally correlates with our detector hardware (ITS) efforts. Heavy quarks uniquely probe the QGP and it is of interest to not only measure and compare heavy-quark production in heavy ion and proton-proton collisions, but also to measure their participation in the collective expansion of the QGP. At the LHC the production rate of heavy quarks is drastically increased with respect to the previous generation of colliders allowing, for the first time in heavy-ion collisions, precision measurements of hadrons containing c and b-quarks. Further measurements at the LHC, after the detector upgrade, will allow us to extend the kinematic range of heavy quark production dramatically and provide us with sufficient data to measure their collective motion (see Fig. 14).

B1.2 Talent case

"This is a place like nowhere else on Earth. As one of the world's largest centres for scientific research, we're using fundamental physics to try and answer some of the biggest questions in the Universe. Nowhere else will you get the chance to work on experiments of this magnitude. Nowhere else do the world's most talented scientists and engineers rub shoulders."

Find out more, a little book about CERN

CERN is a unique place for many people: high-school students attending the annual CERN master class at Nikhef; master students becoming CERN summer students; high-school teachers following a CERN teacher programme to keep up-to-date with the latest developments in particle physics; a lay(wo)man just visiting CERN to get a taste of the scale of today's accelerator experiments; PhD students interested to pursue their curiosity; postdocs aspiring to a CERN fellowship; senior (particle) physicists taking a sabbatical as a CERN associate; or one of the 10,000 registered CERN users. Also, many professionals from *e.g.* high-tech industry, publishers, computer hard- or software firms visit CERN to attend fairs or workshops, or perhaps to develop and/or test new technology. Their interest is not always in experimental particle physics, but also in computer science, accelerator science, detector R&D, theoretical physics, microelectronics, material science, vacuum technology, proton therapy, superconductivity, etc.
Indeed: *There is no place like CERN!*

As coordinating institute of the CERN-related activities in the Netherlands, Nikhef benefits directly from CERN's excellence. Master students from both the Netherlands and abroad attend Nikhef's master programme in Particle and Astroparticle Physics. The PhD school of Subatomic Physics year-upon-year receives more applications than can be funded (enrollment averages about 90 PhD students). After graduation, two-thirds of Nikhef's PhD students pursue a career in private industry (often within the Netherlands), while the rest stays in academic research. Working at the forefront of science turns out to be an excellent starting point for a career elsewhere. Nikhef also has no problem to attract excellent candidates for its postdoc (total formation about 32) and staff positions (60 in total).

For Nikhef to continue to attract excellent scientists to the Netherlands, adequate funding for our LHC programme participation is essential. Capital investment funds (*i.e.* for detector construction and large scale computing) are the hardest to secure. Other expenses are covered by the Nikhef budget (*e.g.* salaries, travel, Nikhef's technical infrastructure) or the Dutch CERN membership fee (CERN infrastructure and in particular the accelerator complex). Without capital investments funds for LHC detector upgrades, Nikhef would jeopardize its excellent detector R&D track record (incidentally also Nikhef's main asset vis-à-vis industrial collaboration) and inevitably at a later stage also its prominent position in LHC data analysis since cutting-edge analyses rely upon a deep insight of not only the physics but also of detector characteristics. This negative trend will be equally severe, if the funding for the continuation of NL/Tier-1 would come into question. This negatively affects also many other research disciplines, because the NL/Tier-1 forms a significant share of the Dutch National e-Science Infrastructure. Nikhef experts develop, build and operate a significant share of this infrastructure, as well as actively facilitate its use outside the context of particle physics, in direct collaboration with scientists from other disciplines as varied as medical imaging, linguistics, bioinformatics, and radio astronomy. The discontinuation of NL/Tier-1, given its prominent position in the worldwide grid infrastructure, would be very poorly aligned with the 2010 decision to locate the headquarters of the European Grid Infrastructure (EGI) in the Amsterdam Science Park. EGI is the organization supported by the EU to coordinate activities between national grid infrastructures in Europe (similar to TERENA for networking, which is also located in Amsterdam). Amsterdam was chosen to host the EGI headquarters to a large extent as a result of Nikhef's (and the Dutch) early involvement and pioneering role in grid-computing technology.

B2 Innovation case

> *"…a theoretical, engineering and organisational feat whose time-horizon, size and complexity make it one of mankind's most ambitious endeavours to date, scientific or otherwise, alongside the Manhattan Project, the Apollo space programme, or America's mobilisation for the second world war."*

The Economist, blog about the LHC project

The primary focus of this proposal is curiosity driven research, in short: "*What is the Universe made of?"* and "*How does the Universe work?"* Nevertheless, our research community has, long time ago, realized that it is vital to make the connection between our research activities and 'third parties', where third parties can be other research disciplines, industry, our youth or our society at large. Thanks to the LHC project and in particular the recent discovery of the Higgs particle, interest in our research is simply overwhelming. Collaboration with industry and the knowledge and technology transfer to other research disciplines, capitalize on the inherently high-tech and almost always cutting-edge technologies required in our experiments. Typical examples are radiation detectors, sensor networks and computing technologies like grid, cloud and hadoop. Some concepts pioneered in our research community have become so successful, with the *World Wide Web* as the prime example, that it is sometimes hard to imagine our society has ever managed without them.

Outreach to general public

Tradionally, our researchers engage in many ways with the general public. In addition to the public lectures and interviews in media like newspapers, magazines, radio and television, our researchers now also perform in science cafés and pop-music temples and even as lecturer on Rhine and Rhône river cruise ships. Even more adventurous are appearances in (physics-oriented) theatre and movie projects, with the highly acclaimed and prize-winning movie titled "*HIGGS –into the heart of imagination"* as the undisputed highlight (Stan Bentvelsen). Another novelty ("*Academische Jaarprijs 2009*; team Sijbrand de Jong) was *Cosmic Sensation* –a multi-day silent disco, with the music and light show steered by and visualizing the passage of cosmic-rays . During the "*Kennismaand"* (science month) our institutes open their doors to share the excitement of our research with the general public. Several of us also consult with (popular) science authors. An excellent example is "*De deeltjesdierentuin"* (The particle zoo) by Jean-Paul Keulen. We are determined to continue, and wherever possible to extend these numerous public outreach activities to further raise public awareness of fundamental curiosity-driven scientific research.

Outreach to youth

Apart from the outreach activities aimed at the general public, we have special programs targeting children and high-school students (and their teachers). For kids we collaborated with the NEMO science museum in Amsterdam to create their hands-on cosmic-ray experience. Our physicists also regularly perform in the NEMO "*Wakker Worden Kinderlezing"* (Wake up Lecture) series targeted at young children (8–12 year). Els de Wolf initiated the very successful "*Techniektoernooi"*, an annual technical competition (paper bridges; balloon cars; air-pressure rockets; *etc.*) for elementary school pupils. We sponsored two episodes, featuring the LHC, for the very popular programme "*Klokhuis*", which aims at explaining all kinds of interesting phenomena to elementary school kids.

Figure 15. The AMS-02 experiment on the International Space Station (ISS) is cooled a CO_2-cooling system, developed and built by Nikhef. A similar CO_2-cooling system was subsequently built for the LHCb experiment and a system for ATLAS is under construction.

To high-school students we offer various activities, including guest lessons at their premises, (CERN) master classes at our institutes, assistance with high-school projects and guided tours to CERN. Frank Linde chairs www.natuurkunde.nl, a website aimed at high-school students with the goal to stimulate interest in science. Nikhef initiated (Charles Timmermans and Bob van Eijk) and runs the HiSPARC (*High School Project on Astrophysics Research with Cosmics*) project in which currently more than 90 schools participate in the Netherlands and a few abroad. Nikhef offers high-school teachers a research internship (one day per week over a one year period) and Nikhef sponsors high-school teachers to enroll in CERN's high-school teacher events. Several Nikhef staff members contributed to the new high-school physics curriculum which was launched September 2013. Sijbrand de Jong is the director of the Radboud Pre-University College of Science, streamlining all high-school-related activities of the Radboud University's faculty of science.

Links through the national e-infrastructure

Nikhef has a long-standing tradition in cutting edge information technology, with internet involvement from the beginning in the early eighties. This resulted in the housing of AMS-IX, one of the World's largest internet exchanges, at Nikhef in the mid nineties. Today Nikhef is still one of the largest of the presently 12 AMS-IX locations, as measured in number of customers (about 120 companies). The societal impact of this activity is unquestionable. The experience of providing a reliable data centre for AMS-IX at Nikhef has paid off enormously in setting up and running the Dutch Tier-1 grid computing facility, which is now part of the national e-infrastructure.

This national e-infrastructure is world class, consisting of several large facilities and many more smaller clusters, linked together by excellent network connections, and providing power via grid computing, cloud computing, high-performance clusters, large-scale storage facilities and a data-mining service. Much of this has grown out of Nikhef's leading role in European projects on distributed computing over the last decade. In this decade, many computing vendors have recognized the innovations being made at Nikhef, having made the observation that what Nikhef asks for now, many others will ask for in a few years. The group is allowed to experiment with pre-market prototypes in order to provide the vendors with valuable insight into what is coming up. Software developed at Nikhef to allow ten thousand physicists, spread across more than 150 particle-physics institutes and over 50 countries and economic regions, to collaborate in sharing data and computing capacity, has been used as the basis for *e.g.* the computing services for CLARIN, the ESFRI project on common language resources and technology infrastructure.

With the end of the BiG Grid project in 2012, Nikhef has passed the lead of this infrastructure on to SURF, where it continues to develop and expand to serve an ever-increasing population of sciences from the Netherlands and elsewhere. Although the services provided have expanded well past the "grid" interfaces used by the LHC community, that community still operates the most demanding computing infrastructure and hence still drives much of the innovation of the infrastructure. Following in the footsteps of the HEP community are thousands of researchers from over 40 distinct communities including astroparticle physics, astronomy, the life sciences, the humanities, civil engineering, and econometric studies. Nikhef contributes an advisor ("integrator") to the *Netherlands eScience Center*, which is charged with expansion of e-science techniques and data-driven research to other important areas such as water management.

Links to industry in general

Our detector R&D activities have demonstrated to be an extremely fruitful and proven breeding ground for valorisation activities, *i.e.* the translation of knowledge into technology to create commercially viable products or services. Nikhef has a long-standing collaboration with PANalytical, a company marketing X-ray diffraction systems with pixel detectors originating from our detector R&D. Nikhef collaborates with the world's leading lithography company ASML on CO_2 cooling applications with very accurate temperature stabilisation. Together with Philips, Nikhef is working on the development of large area X-ray detectors that provide spectral (energy) information. This development is taking place in view of particle therapy, conventional X-ray therapy and cardiac angiography applications.

In 2010, Nikhef founded, together with an investment firm, P2IP (*Particle Physics Inside Products*) as an umbrella organization for start-up companies. In 2011, P2IP launched Sensiflex to market a Nikhef patented alignment concept (RASNIK) for civil engineering applications. ASI (*Amsterdam Scientific Instruments*) was also launched in 2011 and markets custom applications for detector systems at FELs all over the world. With Royal Dutch Shell, Nikhef is engaged in studies of a huge, low-mass and low-power seismic sensor network with wireless readout for oil exploration. This has resulted in another startup, InnoSeis.

Industrial networking

Our industrial liaison officer informs Dutch industrial parties about upcoming CERN tenders. He has organized a successful *'Holland@CERN'* symposium, a three-day long industry event at CERN, where 27 Dutch high-tech companies displayed their products to CERN users, engineers and technicians. Our technical groups (mechanics, electronics, computing) are in constant dialogue with local and European industries. Industrial networking meetings are organized to inform each other on technological advances. Finally, Nikhef has an open policy with regard to giving external parties access to the Nikhef technical facilities, on a cost recovery basis. In this way, our '*Silicon Alley'* facilities for semiconductor detectors, containing equipment for probing, bonding, precision measurement and diagnostic electron microscopy, are used by several companies (*e.g.* PANalytical, ASI, Sonion, Grass Valley).

Figure 16. PANalytical PIXcel detector system, based on single-chip Medipix2 technology, developed in collaboration with Nikhef. The Empyrean X-ray diffractometer in which these detectors are used, received an R&D award of R&D Magazine in 2011.

'Topsectoren'

A few years ago, the Dutch government identified nine areas (*'topsectoren'*) in which the Netherlands excels. One of these areas, *High-tech systems and advanced materials* (HTSM), matches well with our research. The recently added HTSM sub-chapter *advanced instrumentation* is a perfect match for many of our experiments. Through the imaging hardware and software development there is a strong tie to *Life Sciences and Health*. The view held by the Dutch government on innovation:

> *"Innovation is essential for companies that want to grow. The development of new technologies is expensive and requires specialist knowledge. Often it is uncertain whether the technology is successful. This requires a good strategy."*

http://www.rijksoverheid.nl/onderwerpen/ondernemersklimaat-en-innovatie/investeren-in-topsectoren

applies equally well to our own activities in experimental particle physics. Particle physics has become the breeding ground for high-tech development in the areas of data handling, computational science and detection devices. Companies that have been involved with CERN invariably profit from an increase in revenue but maybe even more importantly of know-how. In 2005 CERN compiled an overview of best examples: *"CERN technology transfers to industry and society"* (including *e.g.* PANalytical). Both CERN and Nikhef actively promote and support technology transfer and spin-off activities. The emerging field of astroparticle physics will again provide an area in which innovative technology, be it in the deep sea or in seismic isolation, will come to the forefront. Nikhef will vigorously pursue the transfer of its technology to industry and it is convinced that with the in-house technology and with excellent links to CERN it offers a broad spectrum of opportunities. In this context: Nikhef currently negotiates with CERN the establishment of a *CERN Business Incubation Center* (CERN-BIC) at the Amsterdam Science Park, in conjunction with *Venturelab*, the University of Amsterdam sponsored initiative for scientific startups.

Young, highly trained professionals

Finally, maybe the most important contribution from LHC activities to the 'knowledge economy' are the many well trained and educated PhD students (15 to 20 PhD students graduate annually). Career data from the OSAF Research school show, that while one third of PhDs continue in research, two thirds pursue a career in other sectors, notably in high-tech industries and ICT (*e.g.* the current consultancy group on 'big data' at KPMG is formed almost completely of former Nikhef-PhD students).

"One way for companies to emulate Big Science is to employ more scientists. Simon Williams, co-founder of QuantumBlack, a London-based data consultancy, says his visits to CERN (to seek technical help with number-crunching) prompted him to value PhDs over MBAs. They can be a handful, Mr Williams concedes, but they also require less hand-holding. Give them an interesting problem and they will get cracking, he adds with enthusiasm."

The Economist, Schumpeter, 27-4-2013

"CERN is the place to find top PhDs in physical sciences and computing," said Dominic Connor, head of quantitative finance recruitment firm P&D Quant Recruitment. "Working at CERN is one step up from having any old PhD. There are a lot of people who have doctoral degrees, but you know that if someone has worked at CERN they will be very good indeed."

eFinancialCareers, Butcher, 15-5-2013

B3 The importance for the Netherlands

The opening quote of this proposal leaves no doubt that the LHC is and will remain for more than a decade the world's premier particle-physics research facility. Because of the staggering costs of facilities like the LHC, it is also clear that the next world-wide accelerator project at the energy frontier, an electron-positron linear collider, will only really gain momentum after the LHC has explored the 'terra incognita' of the TeV scale. This explains why a large fraction of the world-wide particle physics community participates in the LHC project (in round numbers: 10,000 scientists from 600 institutes representing 100 nationalities). Nikhef is no exception: 50% of Nikhef's physicists are members of an LHC experiment collaboration whereas another 15% is indirectly connected to the LHC project (detector R&D, grid computing and theory).

	Management positions
ATLAS	Detector upgrade coordinator: N. Hessey Computing coordinator: K. Bos Top-physics convener: S. Bentvelsen, P. Ferrari, W. Verkerke SUSY convener: P. de Jong Muon combined performance convener: P. Kluit B-tagging convener: F. Filthaut
LHCb	Outer Tracker project leader: A. Pellegrino, N. Tuning Vertex Locator project leader: J. v.d. Brand, deputy: E. Jans, M. v. Beuzekom Trigger project leader: G. Raven Operations coordinator: P. Koppenburg (Deputy) Physics coordinator: P. Koppenburg
ALICE	Deputy spokes person: P. Kuijer Upgrade coordinator: Th. Peitzmann Silicon Strip Detector project leader: P. Kuijer, G.-J. Nooren First run coordinator: P. Kuijer

Table 3. Overview of (present and former) key positions of Nikhef staff in the three LHC collaborations.

Nikhef's policy is to engage only in outstanding activities in which Nikhef really makes a difference; *i.e.* can contribute significantly to both the detector hardware (design and construction) and scientific exploitation. The Dutch activities at CERN, coordinated by Nikhef, fit this policy. In all three experimental LHC collaborations Nikhef has shown leadership in the design, construction and commissioning of the now successfully running silicon detector systems. Nikhef made major contributions to more conventional, wire-chamber based tracking systems in LHCb (Outer Tracker) and ATLAS (Muon Spectrometer). Nikhef was and still is at the forefront of the LHC computing infrastructure (WLCG). Nikhef groups are very active in the data analysis, including the important, but less glamorous, tasks of calibration and alignment. Nikhef's international Scientific Advisory Committee (SAC) stated in its report of February 2011 on this topic (see also Table 3):

"Dutch scientists, after making important contributions to the hardware, have kept their prominent position in all collaborations with a very significant (even outsized) role in producing the first physics results. They are very visible and well represented in a number of leadership and management positions, including the position of 'upgrade coordinator' in both ATLAS and ALICE. The SAC congratulates Nikhef and all LHC teams for this outstanding success and looks forward to an exciting and productive LHC exploitation, which should last well into the next decade."

B4 Institutional environment (management case)

Embedding & critical mass

The Nikhef consortium agreement, a collaboration between the national physics funding agency (Fundamental Research on Matter, FOM) and four universities (Radboud University Nijmegen (RU), Utrecht University (UU), University of Amsterdam (UvA) and VU University Amsterdam (VU)), is instrumental in defining the Dutch research agenda in particle (and astroparticle) physics. The Nikhef organization model is often considered as exemplary both within and outside the Netherlands as *e.g.* acknowledged by our government in a letter to Parliament from the Ministry of Education, Culture and Science (OCW) (8 April 2011):

> *"It is important to keep an eye on the special position of the institutes of NWO and the Academy. The long-term commitment of national research resources to research areas that are important for our country, implies a national function that is incompatible with an exclusive arrangement with just one university or university research group. The aim should be to cooperate at a national level. NIKHEF, in which the NWO-FOM foundation works together with four universities, could be a model to follow. The universities participate in funding and are represented in the NIKHEF-board. NIKHEF scientists do not only teach at the participating universities but at all nine universities with a physics department. The NIKHEF-model can be an example how universities, also financially, could take their responsibility in their cooperation with institutes of NWO and KNAW."*

Examples of joint ventures which already use the Nikhef collaboration agreement as a model are: ITER-NL and HFML in the Netherlands and the Helsinki Institute of Physics (HIP) in Finland.

Even in a collaboration it is important that each partner can identify and when possible claim national leadership in some of the collaboration's activities. Concerning the LHC experiments the distribution is as follows: ATLAS (RU and UvA); LHCb (VU); and ALICE (UU). The Nikhef laboratory in Amsterdam constitutes the backbone with technical (mechanics, electronics and computing) departments and state-of-the-art technical infrastructure as well as strong theory, grid computing and R&D groups.

An observation of the Netherlands Observatory of Science and Technology (NOWT) report *"Science and Technology Indicators 2010"* is worthwhile mentioning as well in this context:

> *"Joining forces, through specialized inter-university partnerships and other R&D networks seems to be a success formula for creating economy of scale and hence to reach world top class. As a result, some research Leading Technological Institutes (TTI's) and Nikhef have a big citation impact on international science."*

Governance and quality of the management

Experiments in particle physics belong to 'Big Science': *i.e.* they require substantial budgets and long lead times. The LHC with about 30 years between the first conceptual idea and the first collisions and a construction budget (accelerator only) of about 3 G€ is no exception. Such projects can only be executed successfully and more or less within budget with an excellent governance and management structure. CERN has repeatedly proven to be able to do so by successfully designing, building and operating projects like: PS (1959→present), SPS (1976→present), ISR (1971–1984), Sp$\bar{p}$S (1981–1993), LEP (1989–2000), ISOLDE (1992→present) and now LHC (2009→present). Throughout the history CERN has continuously, partly driven by ever-growing complexity and size of its projects, expanded its base. CERN Council (CERN's top level governance body with representatives of all CERN member states) has opened CERN membership also to countries outside Europe. Hereby CERN is a true worldwide laboratory. And the LHC project is essentially the first global accelerator project, drawing significant contributions to the accelerator and the experiments from Europe, Americas and Asia.

At a smaller scale, the same applies to the Dutch contributions, notably to the LHC detectors and the WLCG project. Nikhef coordinates these efforts within the Netherlands. The efficiency hereof is excellently summarized by the NWO-installed international review panel of world-renowned experts that evaluated Nikhef in 2011:

> *"FOM-Nikhef is one of the leading laboratories in experimental particle physics in the world, with an outstanding record of achievement in detector and electronics design, construction and commissioning, physics analysis and advanced computing techniques, supported by a strong theory group. In addition, through the Nikhef organization, it is more than a laboratory; it is bringing a number of University groups to work together in an integrated*

way since the faculty members are taking larger responsibilities than would have happened if the same resources were spread to a number of independent University groups. Nikhef with FOM-Nikhef in the centre, is a model of efficiency giving the Dutch research a much larger international impact than if the corresponding resources were distributed among a set of independent university groups, and has a strong focussing effect."

Accessibility

Research in elementary particle physics, is and always has been open to any interested party. All LHC experiment collaborations are world-wide collaborations. CERN membership is available to any country interested. Like CERN, also Nikhef welcomes new groups, in 2012 physicists from Groningen University joined the Nikhef LHCb group and Groningen University has recently requested to become a member of the Nikhef consortium. Nikhef's infrastructure serves Nikhef (experimental) research activities, irrespective of the affiliation of the physicists who lead the activity. Nikhef's (grid) computing facilities are available to other research communities.

B5 Financial aspects (business case)

The total cost of Dutch contribution to the LHC detector upgrades, including the NL/Tier-1 continuation, is estimated at about 61.5 M€ during the years 2014 until 2023 (see Budget section). More than two thirds of this will be covered from the Nikhef budget (FOM and university partners). As in the past the LHC efforts will also in the next decade remain Nikhef's main scientific enterprise. FOM-Nikhef will attribute directly a third of its mission budget to the detector upgrade activities (about 3 M€/year). Similarly, the university partners will devote an equivalent of 0.44 M€/year.

For the investments in the detector construction, the national Roadmap is the only feasible source of funding. No co-funding from external sources is to be expected. The investments in the NL/Tier-1 will form part of the total investments in the national e-infrastructure, which is also on the national Roadmap, underlining its importance for national research. However, SURF will not seek funding for this in the current call. It is therefore even more important for user communities, such as our community, to attract investment funds to strengthen the national e-infrastructure.

All requested investments are timely and urgent. The LHC collaborations are currently negotiating their concrete upgrade proposals. Granting the investment now would allow Nikhef to position itself well within the upgrade projects and will secure Nikhef's reputation as a very reliable collaborator. The investments in the NL/Tier-1 are badly needed, because the investments resulting from the BiG Grid project (2007–2012) are reaching the end of their lifetime.

A proposal for the scientific exploitation (PhD-positions and postdocs, travel, maintenance and operations costs) of the LHC experiments for the period 2014–2021 titled *'LHC Physics-the Dutch participation'* for a total of 16,863 k€ was recently granted by FOM. In addition, Nikhef staff will continue to apply for personal grants and project funding, at which they have been very successful in the past.

B6 Technical feasibility/challenges (technical case)

At present, the main focus of the LHC collaborations is on data taking, data analysis and physics publications. However, as already explained in this proposal, efficient and optimal exploitation of the LHC discovery potential does require upgrades of the LHC detectors (of the detectors proper as well as of the grid computing infrastructure provided by WLCG) in the future. We positioned ourselves for these upgrade projects, building upon the expertise we have gained in designing and building the present LHC detectors and the NL/Tier-1 grid compute centre. The specific topics for which we request capital investment are:

- Construction of new sub-detector systems, based on:
  - Design of (silicon pixel and -strip) detector modules;
  - (Co-)development of electronics-readout chips;
  - Industrialization of the CO_2 cooling technology.
- Expansion of the NL/Tier-1 storage- and compute capacity to keep the NL/Tier-1 aligned with the foreseen evolution of the WLCG and to enable the exploitation of data from the upgraded LHC complex.

Before detailing our upgrade plans, we want to emphasize that Nikhef has a long-standing tradition and experience in detector R&D, design and construction. *E.g.* in the field of silicon-detector R&D, testing, characterization and assembly, Nikhef has, over a 10-year span, set up an excellent infrastructure (*Silicon Alley*), including clean rooms, a wafer probing station, wire-bonding robots and a 3D-metrology station. Using CO_2-cooling technology in particle physics experiments is a Nikhef invention. Building silicon-based sub-detector systems is exactly what Nikhef has been doing, in cooperation with groups in other countries, not only for the LHC detectors now in operation, but also for previous experiments at *e.g.* HERA (DESY, Hamburg) and LEP (CERN, Geneva). Like these past projects, Nikhef is confident that the new detector projects can be concluded successfully from the engineering point of view. The main risks are not the technical aspects (the particle physics community's field of expertise), but rather whether or not all international partners will succeed to amass the required investments funds. The second topic, the continuation of NL/Tier-1, requires little in-house hardware development. The challenge here is to design an underlying, robust system in both hardware and software, that is able to sustain the large computing and network load to be expected in the coming years. This is an activity Nikhef is now engaged in for about a decade and it is by hands-on experience that a service like the WLCG has become the success it is at present. Nikhef has every intention to continue this success for at least another decade.

LHC detectors and upgrades
ATLAS

At the foreseen peak luminosity (50 $nb^{-1}s^{-1}$) of the high-luminosity LHC, proton-proton interactions will occur at the astounding rate of about 5 GHz in ATLAS, *i.e.* every 25 ns about 125 overlapping proton-proton interactions will take place. The ATLAS data-acquisition system must reduce this gigantic input rate to about 5-10 kHz, an 'event' rate which is fed into the WLCG for analysis. This is achieved via a step-wise process by first converting the hits of the roughly 700 million detection channels of the upgraded ATLAS detector into physics quantities (ultimately particles *e.g.* a muon flying out from the collision point with measured energy and flight direction, see Fig. 7), to subsequently filter ('trigger') the events of interest. This filtering typically selects events with high transverse activity (energy), the typical signature of massive particles. To reconstruct and identify particles, the ATLAS detector employs several concentric detection layers with each a specific functionality. From inside out: the central tracker embedded in a superconducting solenoidal magnetic field to measure charged particle tracks; the calorimeters to stop most particles thereby measuring their energy; and finally the muon spectrometer embedded in a superconducting toroidal magnetic field to identify and to measure muon tracks. Nikhef made large contributions to the silicon strip tracker, the muon spectrometer and the data-acquisition/trigger electronics.

It is expected that severe radiation damage will impair the detection layers closest to the beam line, *i.e.* (large) parts of the central tracker and parts of the forward muon spectrometer. Furthermore, the high interaction rate will lead to unacceptably high occupancies in parts of the detector, as well as poor performance of the trigger. Therefore ATLAS plans to progressively upgrade some of its sub-detector systems. Already in the 2013–2014 LHC shutdown, ATLAS is installing a new pixel layer inside the present pixel detector. Profiting from the ever smaller feature size in microelectronics, Nikhef designed important parts of the pixel-chip electronics with enhanced intelligence per pixel for this new detector. Nikhef is one of the few particle-physics institutes taking up these rapid technology changes and Nikhef aspires to maintain or even strengthen its expertise in this area. Before entering the LHC high-luminosity regime (*i.e.* following the 2022–2023 LHC shutdown, see Table 2), ATLAS envisages to install a completely new central tracker. It is planned to build a

Figure 17. Nikhef PhD student working on the ATLAS SCT.

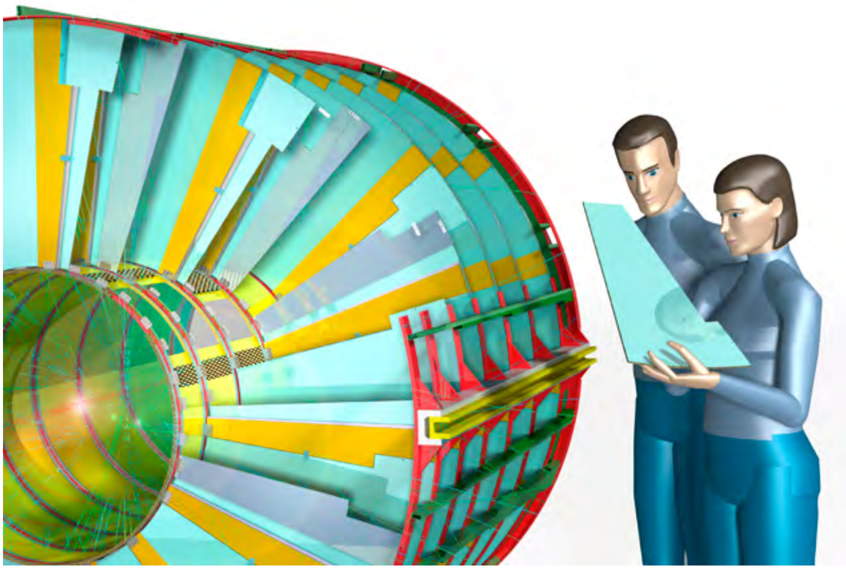

Figure 18. ATLAS: artist's impression of the end-cap of the new silicon-strip tracker (ITk).

much larger silicon tracker profiting again from improved semiconductor technology since the original ATLAS silicon tracker was built. The requested investment budget for the new silicon tracker (ITk) amounts to 4.4 M€.

Nikhef is already engaged in several engineering issues for this new tracker as *e.g.* shown in Fig. 18. The new central tracker will be a cylinder of 6 meters length and 2 meters diameter, consisting of a central barrel and two end-caps at each side, with silicon pixel sensors closest to the interaction point, and silicon strip sensors surrounding the pixel sensors, for a total of 200 m^2 silicon sensors and 700 million electronic channels. Each high-momentum charged particle produced in a proton-proton interaction in ATLAS will typically give 14 consecutive high-precision hits in the new inner detector, enabling particle tracking with excellent momentum resolution even in high-track density environments, and very good vertex identification capabilities. Nikhef intends to construct a significant part of the new tracker in Amsterdam, namely one end-cap of the silicon strip detector. Each end-cap consists of seven disks, and each disk contains 32 'petals': super-modules with nine silicon sensors on each side. An innovative design of the petals and their support structure, involving carbon fibre honeycomb structures and carbon foam with embedded cooling pipes, leads to a very light and stiff structure, minimizing dead material in the detector, and thereby minimizing multiple scattering and unwanted secondary interactions. The strip sensors are n-in-p silicon sensors, the pixel sensors will most likely be planar n-in-n and n-in-p silicon sensors, with 3D silicon or diamond sensors as back-up solution. Nikhef is also testing a very innovative concept using silicon pixels with small super-imposed gas volumes, realized using MEMS (MicroElectroMechanical Systems) technology. Nikhef has designed the CO_2-based cooling system for the new pixel layer to be installed in the 2013–2014 LHC shutdown, and is involved in R&D for a much larger cooling system for the new central tracker.

To cope with the large data rates foreseen at the high-luminosity LHC, Nikhef is involved in the design of a new detector readout architecture. Advanced technology in the form of radiation hard optical links providing a set of independent logical parallel links implemented on the same physical medium by means of the GBT (GigaBit Transceiver) protocol, allows to transfer different logical traffic types (*e.g.* event data, configuration commands, timing signals) on the same physical links. A main principle in this new approach is the evolution from fixed point-to-point connections between front-end electronics and readout and control elements to reconfigurable ones. A new central element in this architecture is an interface module (FELIX: Front-End LInk eXchange) between the GBT links and the system distributing trigger-accept decisions and timing information and the network connecting to the readout and control elements. This architecture is expected to be used for the full ATLAS detector after the phase-II upgrade, but a first version will already be used for the readout of new muon detectors and trigger elements to be installed in the LHC shutdown around 2018. The requested investment budget for these projects (Muon and TDAQ) amounts to 1.7 M€.

LHCb

The LHCb experiment is optimised for the detection of beauty (and charm) decays. Because b-quark pairs are predominantly produced in the forward direction, LHCb is a single-arm forward spectrometer covering the 10-300 mrad angular acceptance around the beam-pipe. The capability to tag displaced vertices from B decays at trigger level is a key feature of the detector design. Around the collision point, the LHCb detector (see Fig. 10) consists of a Vertex Locator (VELO), which comprises a set of silicon-strip detectors located in two half units that are brought close (7 mm) to the beam line each time that the LHC machine declares 'stable beams'. The VELO is followed by silicon-strip tracking stations before and after a warm dipole magnet, in combination with large detection planes of Outer Tracker (OT) straw-tube detectors, to measure particle momentum. In addition to the tracking detectors, ring imaging Cherenkov counters (for charged pion and kaon identification), a calorimeter (for neutral particle identification) and a muon system (for muon identification) complete the LHCb detector.

Figure 19. A Nikhef technician, installing part of the LHCb VELO detector.

The focus of the Dutch group is on the detection and reconstruction of charged particles. Contributing with a relatively large group, Nikhef has been instrumental in the overall LHCb detector concept, and had a major role in the design, construction and operation of the VELO, the OT and the high-level trigger. Our leading contributions are also reflected in long-term leadership positions in the collaboration held by Dutch members.

The main features of the LHCb upgrade –to be implemented during the 2018 LHC shutdown– are a substantial increase in luminosity and a factor 40 increase in detector readout speed, from the current 1 MHz to 40 MHz after the upgrade. This allows for B- and D-decay vertices to be identified at the lowest trigger level, making the trigger more efficient. To improve the measurement resolution and to cope with higher particle flux, the charged particle tracking detectors, the VELO and the Outer Tracker, will be instrumented with new detector planes. Nikhef, as a major contributor to these tracking detectors, will play a major role in these upgrades.

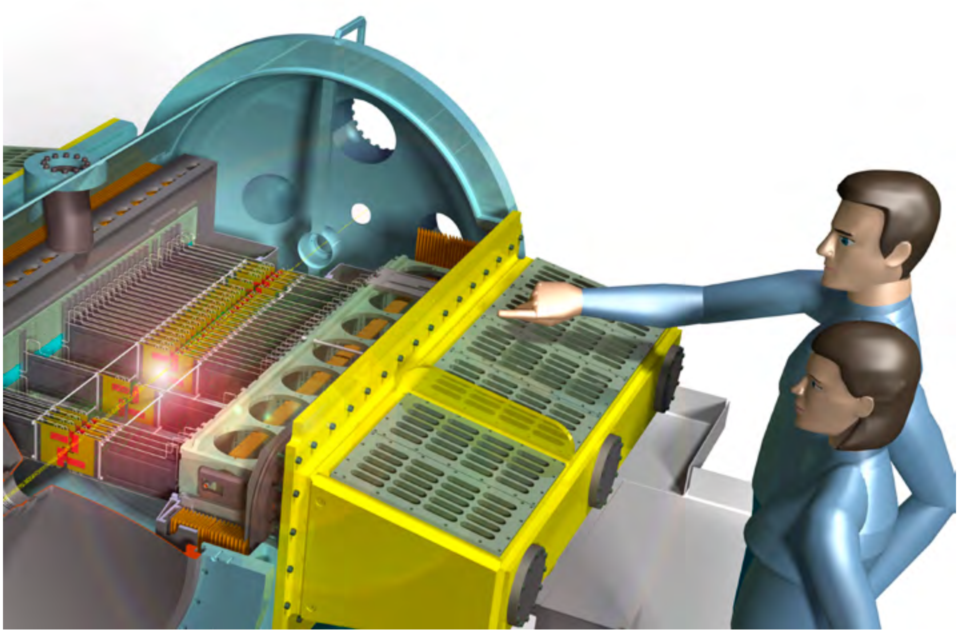

Figure 20. LHCb: Artist's impression of the future VELO pixel modules.

The current VELO silicon-strip detectors will be replaced by 55x55 μm^2 silicon-pixel cells, profiting from Nikhef's extensive experience in developing front-end chips to readout pixel detectors. To improve the vertex detection precision the new detector will be positioned at 5 mm distance from the LHC beam, requiring a new protection and shielding envelope, to be constructed at Nikhef. Similar to the present VELO, also the new detector (see Fig. 20) will make use of the CO_2-cooling technique originally developed by Nikhef and now considered by all LHC experiments for their detector upgrades. Due to its location very close to the interaction point, the detectors will observe huge data-rates corresponding to 300 million traversing particles per second for the VeloPix detector chips, located closest to the beam. The technological challenges include the design of the front-end electronics and the construction of a light-weight detector module that minimizes particle scattering, but also implements sufficient power to cool the electronics and to protect the detector against ageing. The requested investment budget for the VELO, including electronics and detector construction, is 1.5 M€.

For the Outer Tracker, the drift chamber detection technology based on 5 mm diameter straw tubes, will be replaced by 0.25 mm diameter scintillating fibres (see Fig. 21). The improved granularity and hit-resolution of the fibre detector allows for improved pattern recognition capabilities and ensures robust operation at increased collision rates. The superior intrinsic hit resolution of the fibre detector requires that the 5 meter long modules be constructed

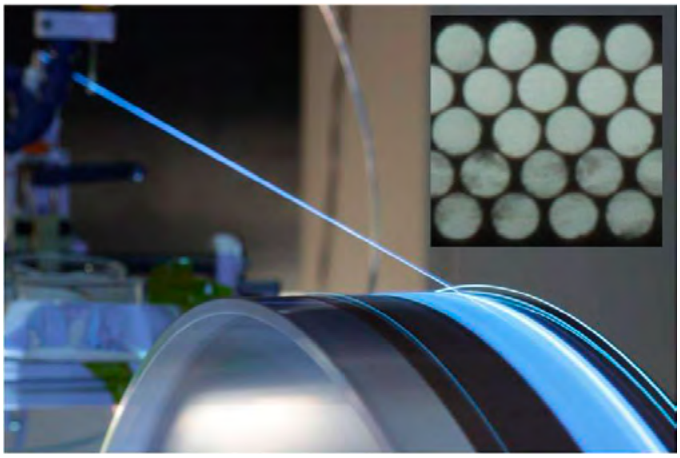

Figure 21. LHCb: spinning of a prototype scintillating fibre detector. The inset shows a cross section of a finished fibre stack.

with mechanical tolerances of 100 μm. Nikhef will become a production centre for producing 5 meter long modules, carrying 20,000 fibres each. The scintillation light of the fibres will be collected using solid state silicon photo-multipliers, which require cooling to -40 °C to prevent radiation damage. Signal digitalization will be performed using an FPGA based design, where the Nikhef group offers leading expertise. The requested investment budget for the Scintillating Fibre Tracker is 2.0 M€.

Finally, to operate at 40 MHz readout cycle, the high-level trigger will be upgraded to a new farm, exploiting large-scale parallel-processing based on multi-core technology (*e.g.* GP-GPU). Nikhef will exploit its leading expertise in the LHCb trigger algorithms and develop parallel algorithms for CPU intensive tasks. The requested investment budget for the trigger, covering the required software development and investment in multi-core computing hardware, is 0.5 M€.

ALICE

The ALICE upgrade strategy matches the LHC plans to after 2018 increase progressively the luminosity for heavy-ion collisions to reach a lead-lead interaction rate of 50 kHz. At this moment the ALICE detector is limited to a readout rate of approximately 1 kHz. The ALICE upgrade will modify the detector such that it will be able to record all interactions. In addition the readout rate capability for proton-proton interactions, which is now also limited to about 1 kHz, will be increased to 100 kHz. Besides a more than two orders of magnitude increase in data collection speed a new, high-resolution, low-material-thickness Inner Tracking System (ITS) will improve the tracking precision significantly and allow access to B mesons and the Λ_c baryon which cannot be separated from background with the current set-up. This new detector, in combination with an upgraded Time Projection Chamber (TPC) and upgraded data acquisition, will allow us to collect about 10^{11} lead-lead interactions in the period 2019-2021, over two orders of magnitude more data than would be possible without the upgrade.

Because of recent progress in silicon-detector technology, it is possible to improve the resolution of the distance of closest approach between a track and the primary vertex by a factor three compared to the present detector. To achieve this, reducing the material budget of the first detection layer is particularly important. In general, reducing the overall material budget of the detector will improve the tracking performance and momentum resolution. In ALICE, the use of *Monolithic Active Pixel Sensors* (MAPS) will allow for a reduction of the silicon material budget per layer by a factor of seven in comparison with the present detector. In addition, a careful optimization of the readout architecture will reduce the power density by at least a factor two, while, at the same time, the pixel density increases by a factor 50. The lower power consumption will allow a factor five reduction in the material budget for electrical power and signal cables. This combination of a new silicon-detector technology (MAPS) with a highly optimized design makes it possible to build a detector with a radiation length (X_0) of only 0.3% X_0 per layer for the first layers of the new ITS (compared to the 1.2% X_0 in the present detector). The material budget for the new outer layers must remain 0.8% X_0 even while the length of the outer layers will be increased by a factor 1.5.

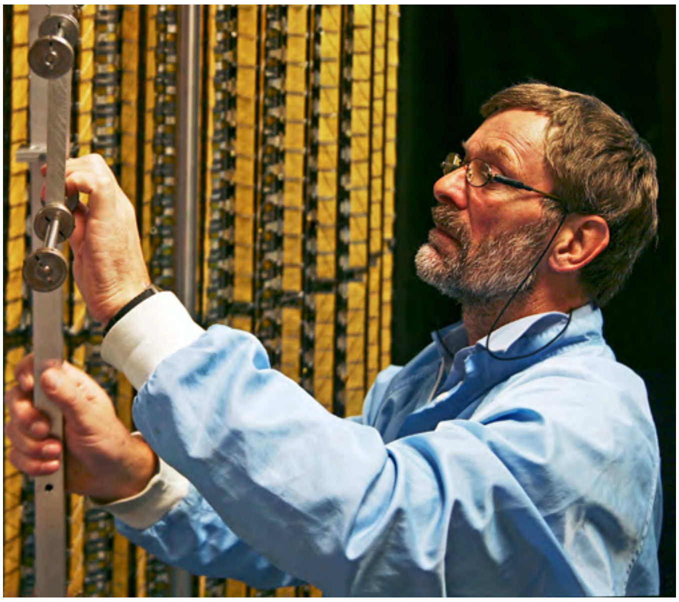

Figure 22. ALICE technician working on the present ITS.

The complete new ITS (See Fig. 23) will consist of seven concentric cylindrical layers of MAPS. The first and the last layer are located at a radial distance of 22 mm and 430 mm from the beam line, respectively. The pixel dimensions of the MAPS are 20x20 μm^2. This configuration will significantly enhance the standalone ITS tracking performance, with a relative momentum resolution of about 2% up to 2 GeV/c increasing to just below 3% at 20 GeV/c. While all layers of the ITS benefit from the new technologies described above, the outer layers will also be made a factor 1.5 longer than the existing layers. This extends the acceptance of the tracking system significantly. However, in order to meet the stringent limits on the amount of material, additional optimizations have to be made for these layers. Since Nikhef played a leading role in the design of the outer layers of the existing tracker (see Fig 23), which is already the lowest mass detector of its kind, we are in the best position to make a larger system with even less material using modern technologies. Nikhef will design and build a serial powering system for the MAPS which will allow reducing the mass of the power cables inside the sensitive volume significantly.

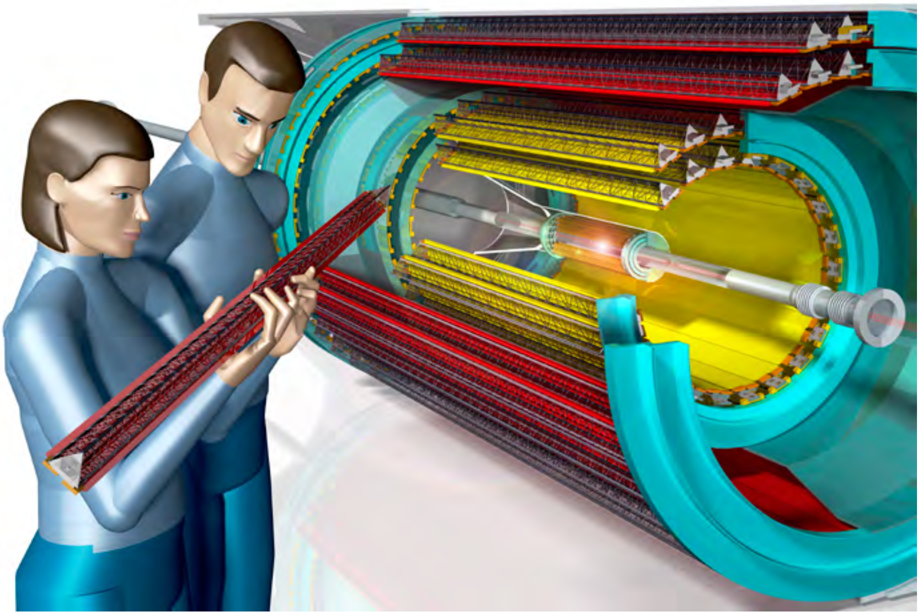

Figure 23. ALICE: Artist's impression of the future ITS.

Such a powering scheme requires development of a specialized ASIC, for which the Nikhef electronics department has the appropriate expertise and experience. Full optimization of this powering scheme can only be achieved with an integrated design and specification of the entire infrastructure connected to the MAPS and therefore the hardware design effort of Nikhef will concentrate on the power, control and signal distribution system for the MAPS in the outer two layers of the ITS, inside as well as outside the active volume. In addition, the cooling system will also represent a significant fraction of the material in the active volume. Nikhef will design and build a cooling system based on CO_2 evaporative cooling with which the institute has ample experience, both for experimental and industrial environments. An evaporative cooling system can achieve a high cooling power with much less cooling liquid than the currently used water cooling system. During the production phase Nikhef will assemble a significant fraction of the detection staves for the two outer layers, using components produced in other laboratories, and assure the quality of the final product in accordance with the foreseen project leadership of Nikhef. The availability of a large and well equipped clean room and a 3D coordinate-measuring machine at Nikhef makes our institute especially suitable for this task. The requested investment budget for the ITS is 2.3 M€.

Detailed simulations have shown that the improved resolution and significant increase in statistics should be sufficient to address the main questions about heavy-flavour thermalization and in-medium energy loss. This total upgrade proposal for the central barrel has been approved by the ALICE collaboration and by the LHCC.

NL/Tier-1

Nikhef physicists and computer scientists, building upon a strong track record in cutting edge information technology, started working on the grid computing concept more than a decade ago as soon as it became clear that the LHC computing needs surpassed the capacity of a single large central facility. The approval of the BiG Grid, the Dutch e-Science Grid, proposal[1] in 2005 made it possible for the Netherlands to join the elite group of countries aspiring to provide a LHC Tier-1 centre. The aspiration was realized in 2006 when Nikhef officially signed the WLCG

1 The BiG Grid proposal was submitted by NCF (Netherlands National Computing Facilities foundation), NBIC (Netherlands Bioinformatics Centre) and Nikhef.

Memorandum of Understanding for providing a Tier-1 centre: NL/Tier-1. The NL/Tier-1 is a joint venture of Nikhef and SURFsara, serving the three LHC experiments in which Nikhef participates (ATLAS, LHCb, and ALICE), and is fully integrated into the Dutch e-infrastructure, operated by the SURF foundation and partners, one of which is Nikhef. SURFsara is the national computer centre and the flagship partner of the national e-infrastructure. The NL/Tier-1 profits from excellent high-speed optical links provided by notably SURFnet. Being the best-connected Tier-1 centre, it plays an important role in the WLCG high-bandwidth network connectivity between several other Tier-1s and CERN.

Since the end of the BiG Grid project, the NL/Tier-1 has received direct investment subsidy from SURF to allow replacement of essential hardware. SURF, through SURFsara, has also ensured coverage of the running costs of the infrastructure and personnel, since the NL/Tier-1 is operated as an integral part of the national e-infrastructure. However, since the roadmap for the national e-infrastructure clearly foresees that investment funding for this e-infrastructure will be channeled through the participating research domains, there have been no investments in expansion of capacity for the NL/Tier-1 since 2011. In replacement of existing capacity (replacing hardware that becomes unsupported and unreliable after four years of service) we have, as requested by the experiments, emphasized at that time storage over computing, hence the gradual increase of storage vs. computing from 2011 to 2013. Fortuitously this 'stand-still' came almost simultaneously with the long LHC shutdown.

Expansion of the NL/Tier-1 to keep pace with the computing needs of the upgraded LHC facility depends on our success in securing new funding. In the new e-infrastructure model, it will be exclusively our own funding that provides the adequate compute and data capacity. However, we will provide this capacity by participating in and through the national e-infrastructure, which allows us to benefit from economies of scale and profit from the joint operations and sharing of personnel. It allows us to focus on investments in capacity, while being assured of the long-term sustainable services by SURF and its subsidiaries.

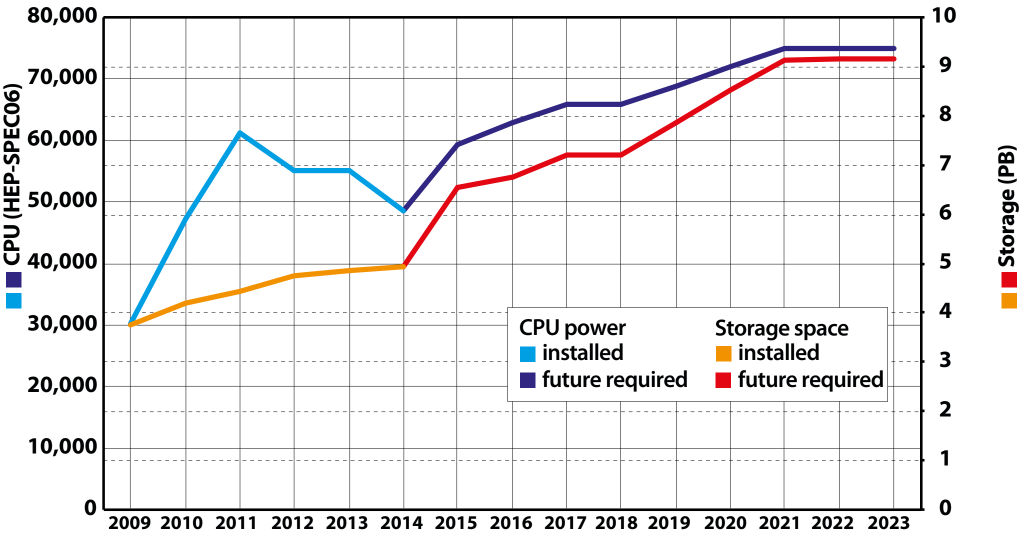

Figure 24. Evolution of the collective storage- and compute capacity at Nikhef's NL/Tier-1 centre. Computing power is presented in HEP-SPEC06 units, a standard derived (to resemble LHC computing) from the industry-standard benchmark suite ('SPEC'). On average one CPU-core corresponds to about 12 HEP-SPEC06 units.

Fig. 24 shows the projected (and historical) growth of the NL/Tier-1 infrastructure of the WLCG. The "future required" growth shown, depends on the NL/Tier-1 share of the stated requirements from the experiments for 2014 and 2015. Past that point, we have extrapolated the growth based on observed historical trends. We have also taken into account (by zero growth) the planned shutdowns in 2018 and 2022-2023, and have revised our relative computing contribution to the world-wide Tier-1 capability of the experiments, taking into account the addition of a 12th ATLAS Tier-1 facility in 2014 in Russia. The uneven investment profile is due mostly to the large increases requested by the experiments for 2015; this increase continues to show up in the investment profile every four years, as the profile includes the standard practice of replacing (outdated) CPUs after four years of operation, by significantly more powerful (Moore's Law) and more (energy-)efficient CPUs. The requested investments are: 2.5 M€ for CPUs, 2.3 M€ for networking equipment and 1.2 M€ for disk and tape storage.

The resource profile depicted, when deployed at the NL/Tier-1, will maintain our essential contribution to the WLCG infrastructure, and will continue to provide Dutch physicists excellent access to the LHC data.

Budget

The budget as shown in Tables 5 and 6 consists of:

- The investments in the detector upgrades (12.4 M€): 6.1 M€ for ATLAS, 4.0 M€ for LHCb, and 2.3 M€ for ALICE;
- The investments in the hardware for the NL/Tier-1 computing and data facility (6.0 M€);
- The personnel costs for the detector construction and the NL/Tier-1 operation (34.5 M€);
- The non-personnel costs (8.6 M€): maintenance and operations costs for the experiments (4.1 M€), detector R&D costs (1.5 M€) and housing costs for the NL/Tier-1 at Nikhef (3 M€).

These budget lines are explained in more detail below.

Detector upgrade investment costs

The substance of the investment costs for the three LHC upgrades is given in the following collaboration documents, that have been reviewed by the LHCC (see timetable section):

- ATLAS Letter of Intent – Upgrade Phase-I: https://cds.cern.ch/record/1402470 ;
- ATLAS Letter of Intent – Upgrade Phase-II: https://cds.cern.ch/record/1502664 ;
- LHCb Framework for the Upgrade - Technical Design Report: https://cds.cern.ch/record/1443882 ;
- ALICE Letter of Intent for the Upgrade: https://cds.cern.ch/record/1475243 .

These documents contain details on the upgrades for the various subdetectors (including the ones Nikhef aspires to be involved in), planning and costs. The investment costs relate to actual expenditure for hardware (electronics, mechanics, etc.) and associated subcontracted work. Based on these documents Table 4 shows the total investments, the investments in the relevant subdetector systems and the proposed Dutch contributions, spending periods and milestone years. Also, our main collaborating partners are listed. The total investment budget of ATLAS, LHCb and ALICE is estimated to be in the order of 341 M€. The Dutch contribution to the individual subprojects as proposed is 12.4 M€, or 3.6% of the total budget (341 M€), commensurate with the present Dutch contribution to CERN and is also very well in line with the Dutch contributions to the initial detector construction in the 1999–2007 period. These amounted to 19 M€; representing also 3.6% of the 520 M€ original costs of all three detectors together.

The proposed Dutch investments as percentage of the total represent 2.3% in ATLAS, 8.7% in LHCb, and 6.6% in ALICE. Within each experiment the investments are targeted at specific subsystems, in which the Dutch contributions represent mostly significantly larger fractions (ranging from 3% in some ATLAS subdetector to almost a third of the LHCb VELO investments).

NL/Tier-1 investment costs

Until 2014, the NL/Tier-1 investments have been covered, mostly by the BiG Grid project. The BiG Grid infrastructure has been taken over by SURF, through its subsidiary SURFsara (computing and data infrastructure). The NL/Tier-1 is jointly hosted by SURFsara and Nikhef and is integrated in the national e-infrastructure serving a wide variety of scientific communities. A large part of the running costs (manpower, housing) is and will therefore be born by SURFsara. The background of the requested investment funds and its spending profile can be found in section B6 technical case. We will channel these investment funds through SURFsara to build on top of the national e-infrastructure.

Personnel costs

The costs for personnel are the sum of all scientific and technical manpower involved in the design and construction activities, totalling 34.5 M€ over 10 years. Permanent scientific staff (estimated at 105 k€/fte year) involved in the upgrades and computing activities will amount to on average 16 fte/year, consisting of a large fraction of the R&D group and the Physics Data Processing group and of about a third of the (three) physics groups. Also about four postdocs and seven PhD-students from the recently acquired FOM-programme *'LHC Physics'* will work on upgrade activities (all other temporary scientific positions from this FOM-programme will be dedicated to the LHC analysis activities). The effort from the technical departments (costed at about 70 k€/fte year) assigned to work on the upgrade projects is on average 22 fte/year over the 10-year period of this proposal with most activities in the first five years (then between 25 to 30 fte/year), notably for the LHCb and ALICE-upgrades, that need to be finished before 2018. The ATLAS-upgrade work is estimated at 100 man-years, the LHCb-effort at about 60 man-years and the ALICE-work around 30 man-years. Furthermore, about 3 fte/year from the Nikhef computing group will be dedicated to the NL/Tier-1 computing operations (30 man-years over the entire project period).

Non-personnel costs

A budget for non-personnel costs is needed to continue the contributions to the maintenance and operations (M&O) funds for the LHC detectors during 2014–2023. These costs —on average about 400 k€/year (4.1 M€ over the 10 year period)— are covered from the associated FOM-programme. Other non-personnel costs are the costs for detector R&D (such as for prototyping), estimated at about 1.5 M€ over a 10 year period. These costs will be born by Nikhef's mission budget. Finally, based on the past 5 years, the cost for housing (infrastructure, electricity and cooling) the NL/Tier-1 part at Nikhef is estimated at 300 k€/year (3 M€ over the 10 year period).

Project	Cost	NL-contribution	Time frame	Installation	Main partners
ATLAS - Muon Phase-I	9,200 k€	400 k€ (4.3%)	2014–2018	2018	CERN, Freiburg, Saclay/Paris, Weitzmann/Israel, SLAC/USA, Michigan
ATLAS - Muon Phase-II	16,500 k€	600 k€ (3.6%)	2018–2023	2023	
ATLAS - TDAQ Phase-I	8,780 k€	200 k€ (2.3%)	2014–2018	2018	CERN, Mainz, Brookhaven, RAL/UK, KEK/Japan, Tokyo
ATLAS - TDAQ Phase-II	20,000 k€	500 k€ (2.5%)	2018–2023	2023	
ATLAS - Inner Tracker Phase-II	130,000 k€	4,400 k€ (3.4%)	2014–2023	2023	DESY/Hamburg, Freiburg, Valencia, CERN, Prague, Uppsala
ATLAS - other subsystems	75,520 k€	0 k€ (0%)			—
Total ATLAS - LoI Phase-I & II	**260,000 k€**	**6,100 k€ (2.3%)**			
LHCb - VELO	4,525 k€	1,500 k€ (33.1%)	2014–2018	2018	Liverpool, Manchester, Oxford, CERN, Glasgow, Santiago de Compostela
LHCb - OT/Scintillating Fibre	11,583 k€	2,000 k€ (17.3%)	2014–2018	2018	Heidelberg, Dortmund, CERN, Lausanne, KNRC/Moscow, Rio de Janeiro
LHCb - Trigger	2,604 k€	500 k€ (19.2%)	2014–2018	2018	CERN, Dortmund
LHCb - other subsystems	27,288 k€	0 k€ (0%)			—
Total LHCb - Upgrade TDR	**46,000 k€**	**4,000 k€ (8.7%)**			
ALICE - Inner Tracker	13,333 k€	2,300 k€ (17.3%)	2014–2018	2018	CERN, Torino, IPHC/ Strassbourg, LNF/Roma, St. Petersburg, Padova
ALICE - other subsystems	21,667 k€	0 k€ (0%)			—
Total ALICE - LoI	**35,000 k€**	**2,300 k€ (6.6%)**			
Total ATLAS-LHCb-ALICE	**341,000 k€**	**12,400 k€ (3.6%)**			

Table 4. An overview of the detector investments, the proposed Dutch contributions, spending periods and main partner institutes.

Risks

Cost risks are inherent to any large investment in scientific equipment. From experience we know these can emerge: the LHC experiments and notably the ATLAS experiment encountered cost overruns during detector construction (1999–2007). These have been addressed collectively within the collaborations by a combination of detector staging, descoping and attracting additional (emergency) funds. Also Nikhef has been able to overcome these cost overruns, *e.g.* by providing extra funds from its mission budget.

Each LHC collaboration itself provides an important risk mitigation measure, namely risk sharing. The collaborations will evaluate possible cost overruns in detector subsystems against their contributions to the potential physics outcome. Common funds or common maintenance & operations budgets will be used to spread financial risks.

I: Total costs of the facility	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	TOTAL
Construction and investment costs											
Detector upgrade - ATLAS - total	120	250	450	1,050	1,050	1,050	1,150	980			**6,100**
Detector upgrade - LHCb - total		1,350	1,950	700							**4,000**
Detector upgrade - ALICE - total		500	1,650	150							**2,300**
NL/Tier-1 investments	500	1,170	230	420	280	1,140	500	280	270	1,210	**6,000**
Total investment costs	**620**	**3,270**	**4,280**	**2,320**	**1,330**	**2,190**	**1,650**	**1,260**	**270**	**1,210**	**18,400**
Running costs											
Personnel costs											
Detector construction - ATLAS	1,008	1,113	1,124	1,197	1,548	1,570	1,518	1,518	1,426	1,019	**13,041**
Detector construction - LHCb	1,965	2,099	1,722	1,526	1,238	733	438	333	228	228	**10,510**
Detector construction - ALICE	540	625	730	730	575	350	280	280	280	280	**4,670**
Detector R&D	315	315	315	315	315	315	315	315	315	315	**3,150**
NL/Tier-1 operations	315	315	315	315	315	315	315	315	315	315	**3,150**
Total personnel costs	**4,143**	**4,467**	**4,206**	**4,083**	**3,991**	**3,283**	**2,866**	**2,761**	**2,564**	**2,157**	**34,521**
Non-personnel costs											
Maintenance & Operations - ATLAS	191	191	191	191	191	191	191	191	191	191	**1,910**
Maintenance & Operations - LHCb	126	126	131	131	131	126	126	126	126	126	**1,275**
Maintenance & Operations - ALICE	86	86	91	91	91	86	86	81	81	81	**860**
Detector R&D	150	250	300	250	200	200	100	100			**1,550**
NL/Tier-1 housing	300	300	300	300	300	300	300	300	300	300	**3,000**
Total non-personnel costs	**853**	**953**	**1,013**	**963**	**913**	**903**	**803**	**798**	**698**	**698**	**8,595**
Decommissioning costs (not applicable)											
Decommissioning costs	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**n.a.**
Other costs (not applicable)											
Other costs	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**n.a.**
Total running costs	**4,996**	**5,420**	**5,219**	**5,046**	**4,904**	**4,186**	**3,669**	**3,559**	**3,262**	**2,855**	**43,116**
Total: construction & running costs	**5,616**	**8,690**	**9,499**	**7,366**	**6,234**	**6,376**	**5,319**	**4,819**	**3,532**	**4,065**	**61,516**

Table 5. Total foreseen investment costs (k€).

II: Non-NWO contributions	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	TOTAL
Applicants											
Personnel costs											
FOM-Nikhef (ATLAS, LHCb, ALICE)	3,712	4,036	3,764	3,609	3,517	2,809	2,445	2,340	2,143	1,736	**30,111**
UvA (ATLAS)	210	210	221	242	242	242	242	242	242	242	**2,335**
RU (ATLAS)	63	63	63	74	74	74	21	21	21	21	**495**
VU (LHCb)	53	53	53	53	53	53	53	53	53	53	**530**
UU (ALICE)	105	105	105	105	105	105	105	105	105	105	**1,050**
Non-personnel costs											
Maintenance & Operations	403	403	413	413	413	403	403	398	398	398	**4,045**
Detector R&D	150	250	300	250	200	200	100	100			**1,550**
NL/Tier-1 housing	300	300	300	300	300	300	300	300	300	300	**3,000**
Total	**4,996**	**5,420**	**5,219**	**5,046**	**4,904**	**4,186**	**3,669**	**3,559**	**3,262**	**2,855**	**43,116**

III: Requested from NWO	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	TOTAL
Detector upgrades and NL/Tier-1 investments	**620**	**3,270**	**4,280**	**2,320**	**1,330**	**2,190**	**1,650**	**1,260**	**270**	**1,210**	**18,400**

Table 6. Total foreseen non-NWO contributions (II) and requested funds from NWO (III) in k€.

Timetable

Duration of the project:	10 years
Planned starting date:	01–01–2014
Expected completion date:	31–12–2023

The major detector upgrade related milestones of this proposal (installation of the various sub-detector systems at CERN) are imposed by the LHC shutdown schedule as detailed in Table 2 and summarized in Table 4. Successful completion of these projects requires not only the Dutch contribution, but of course also the contributions from our (many) international partners and notably our partners indicated in Table 4. This is organized as follows:

- Firstly each collaboration (ATLAS, LHCb and ALICE) converges on its specific detector upgrade plan. This process evolves via *Letters of Intent, Conceptual Design Reports* to *Technical Design Reports* detailing the various sub-detector upgrades, including their cost. This process has largely completed, *i.e.* the detailed upgrade ambitions, costs and often also the desired sharing of work is known (see Fig. 25);
- Secondly the so-called *Resources Review Boards* (RRBs), a CERN installed body with one representative per collaborating funding agency for each experiment scrutinize, approve and monitor the upgrades. The scientific and technical scrutiny is based on the recommendations of the *LHC-committee* (LHCC), a body of independent international experts. The budgetary scrutiny is based on the assessment of another expert committee. Since many decades, this procedure has proven to work efficiently and effectively. The ATLAS Phase-I, LHCb, and ALICE upgrade plans are very close to RRB approval. The ATLAS Phase-II upgrade (new central tracker, scheduled for installation in 2022-2023) is still on the ATLAS-RRB agenda (in particular because of the substantial financial resources required).

In view of the often extensive preparation, construction, installation and commission time, the actual work on the upgrades of the LHC experiments has already started or must start in the coming year. This applies to the largest and most costly single Dutch contribution: the construction of the ATLAS semiconductor tracker (ITk) endcap, scheduled for installation in the long 2022–2023 LHC shutdown. Nikhef and DESY (Hamburg) intend to collaborate closely within the ITk project, since both institutes are expected to deliver an ITk endcap (one on either side of the interaction point). To do so requires firm commitments and hence funding. The same holds for the LHCb and ALICE upgrades since they must be installed already in 2018 (see Table 4). Also, the sharing of responsibilities between the various international partners can only be really achieved once the available funding is known.

Unlike the detector upgrades, the upgrades of the NL/Tier-1 grid compute facility is a more continuous process: obsolete hardware is replaced by ever more performing (and less power consuming!) components, thereby gradually increasing the installed CPU power and storage space to keep up with the increasing LHC data samples. Our request is here not only driven by our own (LHC) specific needs, but also by the desire to keep the Netherlands at the forefront of state-of-the-art (grid) computing. Access to the NL/Tier-1 is open to other research disciplines as well.

Finally, the LHC long-term future, *i.e. High-Luminosity LHC* (HL-LHC) running scheduled to start after the 2022–2023 shutdown with the aim to deliver at least 3000 fb^{-1} to the ATLAS experiment, requires extensive investments in CERN's accelerator infrastructure. CERN Council (the highest CERN body with one delegate from each CERN member state) has already approved 80% of the required resources (identified within the regular CERN budget) by its recent approval of CERN's latest *Mid Term Plan*. This means that HL-LHC is from the accelerator point of view largely funded, on course and on schedule. The experiments have to make sure they meet this schedule in order to benefit fully from the steadily improving performance of the LHC! This is why we submit our funding request now.

Figure 25. A selection of the covers of documents detailing the upgrade plans of the LHC-experiment collaborations.

Declaration and signature

Have you requested funding for this research elsewhere?

☑ No

Declaration

☑ By submitting this form through Iris, I declare that I have completed this form truthfully and completely.

Prof.dr. F.L. Linde (Nikhef director)

Prof.dr.ir. P.J. de Jong (ATLAS programme leader, UvA)

Prof.dr. M.H.M. Merk (LHCb programme leader, VU)

Prof.dr. R.J.M. Snellings (ALICE programme leader, UU)

Prof.dr. N. de Groot (ATLAS programme leader, RU)