FOM programme proposal 2013

LHC physics

the Dutch participation

NIKHEF

1 LHC physics: *the Dutch participation*

CERN's Large Hadron Collider (LHC) is the World's largest research endeavor, spanning –once completed– half a century. The Dutch research community of nearly 40 staff scientists decided early on to focus its LHC participation on three complementary experiments:

ATLAS to explore the **energy frontier** with as primary aim the discovery of new particles and/or new phenomena. The specific Dutch research focus (detailed in Section 4.5) is on: properties of the recently discovered Higgs particle; the direct search for physics beyond the Standard Model, notably (but not exclusively) supersymmetric particles; and work on the new central tracker. For this 18 PhD and 6 postdoc positions are requested.

LHCb to explore the **intensity frontier** using the abundantly produced beauty states to investigate the details of matter-antimatter asymmetry. The specific Dutch research focus (detailed in Section 4.6) is on: the indirect search for physics beyond the Standard Model via detailed studies of CP-violation in selected key processes and via a study of extremely rare or even forbidden decays within the context of the Standard Model; and work on the new tracking system and innovative triggering concepts. For this 12 PhD and 4 postdoc positions are requested.

ALICE to explore the **density frontier** by colliding lead-ions to study the state of matter as it probably appeared in the very early Universe. The specific Dutch research focus (detailed in Section 4.7) is on: flow and heavy flavour production studies in heavy-ion collisions; and work on the new central tracker. For this 10 PhD and 3 postdoc positions are requested.

Section 2 gives a brief overview of the LHC project, Nikhef and the importance of this funding request for Nikhef. Section 3 lists the applicants. Section 4 starts with a concise overview of particle physics and the LHC project. Next the status of the LHC at Nikhef and within the context of the recently updated European Particle Strategy is outlined. The detailed scientific research program is presented in Sections 4.5 (ATLAS), 4.6 (LHCb) and 4.7 (ALICE). Sections 5, 6 and 7 outline the management, budget and societal relevance of this program, respectively. Section 8 gives references. The appendix contains mini-CVs of the applicants.

Nikhef is the National Institute for Subatomic Physics in the Netherlands, in which the Foundation for Fundamental Research on Matter, the University of Amsterdam, VU University Amsterdam, Radboud University Nijmegen and Utrecht University collaborate. Nikhef coordinates and supports most activities in experimental particle and astroparticle physics in the Netherlands.

Nikhef participates in experiments at the Large Hadron Collider (LHC) at CERN, notably ATLAS, LHCb and ALICE. Astroparticle physics activities at Nikhef are fourfold: the ANTARES and KM3NeT neutrino telescope projects in the Mediterranean Sea; the Pierre Auger Observatory for cosmic rays, located in Argentina; gravitational-wave detection via the Virgo interferometer in Italy, and the New Gravitational wave Observatory and Einstein Telescope initiatives; and the direct search for dark matter with the XENON detector in the Gran Sasso underground laboratory in Italy. Detector R&D, design and construction take place at the laboratory located at Science Park Amsterdam as well as at the participating universities. Data analysis makes extensive use of a large-scale grid facility (including an LHC Tier-1 site) operated jointly by Nikhef and SURFsara. Nikhef has a theory group with both its own research programme and close contacts with the experimental groups. Nikhef vigorously pursues knowledge and technology transfer to industry and society.

2 Executive Summary

The Large Hadron Collider (LHC) at CERN, being World's most powerful particle accelerator, is installed in a 27 km circumference underground ring straddling the border between Switzerland and France near Geneva[1]. Two counter rotating beams of particles are accelerated to world-record energies to collide at four locations along the ring. At each of these locations huge particle detectors (ATLAS, ALICE, CMS and LHCb) are installed to record the collision products to study elementary particles and their interactions. The foci of the LHC physics programme are: the detailed investigation of the recently discovered Higgs particle (ATLAS & CMS), supposed to be responsible for all known elementary particle masses; the nature of the minute matter-antimatter differences (primarily LHCb), 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 (primarily ALICE), a state of matter assumed to have existed briefly after the Big Bang; and –last but not least– a search for physics beyond the so-called Standard Model (all four experiments), the immensely successful theoretical framework accurately describing a wealth of experimental observations but notoriously falling short in explaining the nature of the mysterious dark matter in the Universe. The LHC will dominate these (and many other) particle physics studies for at least another decade. The recently adopted update of the European Particle Physics Strategy[2] features the LHC project as its highest priority project.

Nikhef, the *National Institute for Subatomic Physics*, coordinates the Dutch activities at CERN. Nikhef was a founding member of the general purpose ATLAS experiment (1991) and the LHCb experiment (1994) dedicated to the study of matter-antimatter differences in systems with b-quarks. In 1994, Nikhef joined the ALICE experiment optimized to study the quark-gluon plasma. Over the past decades, Nikhef has made major contributions to the design, construction, commissioning and operation of these three detectors as well as to the simulation and reconstruction software needed to extract physics results from the immense data samples. With one of the about ten worldwide Tier-1 LHC grid compute centres housed jointly by Nikhef and SURFsara, Nikhef also plays a key role in the LHC data handling management. All these efforts would have been impossible without the three FOM LHC programmes for the appointments of PhD students and postdocs and to cover membership fees and travel allowances:

Physics at the TeV scale: ATLAS (1997–2016), Relativistic heavy-ion physics: ALICE (1998–2014) and Physics with b-quarks: LHCb (1999–2015).

This long-term FOM support started to really pay-off with the successful start of LHC operations in 2009. Since then, these LHC programmes annually average about 10 PhD defenses and hundreds of publications in refereed journals. So far, the undisputed highlight has been the discovery of the hitherto elusive Higgs particle in 2012. With this the LHC already achieved Nobel Prize quality research, based on only 1% of the aimed-for integral LHC data sample and at about 50% of the design centre-of-mass energy. At this moment, the LHC is in shutdown to implement modifications to notably the super-conducting magnets to allow safe LHC operations at the full design centre-of-mass energy of 14 TeV. The LHC restart is scheduled for 2014 with centre-of-mass energies in the 13–14 TeV region and with a beam intensity ('luminosity') which is expected to gradually increase to even surpass the design 10 $nb^{-1}s^{-1}$ luminosity[3]. After another long shutdown in 2021–2022, the LHC intensity will be increased even further to allow to accumulate the full (3000 fb^{-1}) data sample by around 2030. With these prospects, the LHC is, after decades of preparations, in an excellent position to unveil and explore the TeV energy scale in the years to come! ATLAS' primary goals will be to assess the intricacies of the Higgs mechanism, to better understand the electroweak symmetry breaking and thereby the origin of the elementary particle masses and to search for direct evidence of physics beyond the Standard Model, notably by discovering new, *e.g.* supersymmetric, particles or new phenomena like the creation of mini black-holes. LHCb will further push the already impressive precision achieved in the determination of specific characteristics of systems with b-quarks in order to hopefully discover hints of physics beyond the Standard Model. ALICE will continue complementary studies of quarks and gluons under extreme conditions by colliding heavy (lead) ions instead of protons.

To capitalize on our significant past investments and to allow a continuous Dutch presence at the forefront of accelerator-based particle physics, *i.e.* at CERN's (and the World's) flagship project: the Large Hadron Collider project, a new FOM programme is indispensable. This FOM programme will also be essential for the training of a large fraction of the next generation of PhD students in subatomic physics, *i.e.* the future of Nikhef and of the Dutch activities at CERN. For the period 2014–2021 we request funds for the three experiments from the regular FOM programme to hire PhD students (ATLAS 18, LHCb 12 and ALICE 10) and postdocs (ATLAS 6, LHCb 4 and ALICE 3). In addition, Nikhef aspires to compete for additional funding via various FOM, NWO and EU open competition subsidy programs, to maintain the overall LHC effort in the Netherlands at its current level.

1 See cover illustration.
2 Drafted in January 2013 in Erice (Italy) by the European Strategy Group and adopted by CERN Council on 30 May 2013 in Brussels (Belgium).
3 A luminosity of 1 nb^{-1} means that for a process with a cross section of 1 nb one event on average is collected.

3 Applicants

Applicants

Prof.dr. Frank Linde[1,3], Prof.dr. Paul de Jong[3], Prof.dr. Nicolo de Groot[2], Prof.dr. Marcel Merk[1,6], Prof.dr. Antonio Pellegrino[1,4], Prof.dr. Raimond Snellings[5], Prof.dr. Thomas Peitzmann[5]

1. FOM-Nikhef
2. Radboud University Nijmegen
3. University of Amsterdam
4. University of Groningen
5. Utrecht University
6. VU University Amsterdam

Designated program leader and contact person

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Staff members per subprogramme

ATLAS

Program leaders: Paul de Jong (UvA) & Nicolo de Groot (RU)
Stan Bentvelsen (UvA), David Berge (UvA), Gerjan Bobbink (FOM), Sascha Caron (RU), Pamela Ferrari (FOM), Frank Filthaut (RU), Nigel Hessey (FOM), Olga Igonkina (FOM), Peter Kluit (FOM), Els Koffeman (FOM & UvA), Adriaan Konig (RU), Jos Vermeulen (UvA), Wouter Verkerke (FOM), Marcel Vreeswijk (UvA), Ivo van Vulpen (UvA)

LHCb

Program leader: Marcel Merk (FOM & VU)
Deputy program leader: Antonio Pellegrino (FOM & RuG)
Martin v. Beuzekom (FOM), Wouter Hulsbergen (FOM), Eddy Jans (FOM), Patrick Koppenburg (FOM), Gerco Onderwater (RuG), Gerhard Raven (VU), Niels Tuning (FOM), Leo Wiggers (FOM), Hans Wilschut (RuG)

ALICE

Program leader: Raimond Snellings (UU)
Deputy program leader: Thomas Peitzmann (UU)
Michiel Botje (FOM), Paul Kuijer (FOM), Marco van Leeuwen (FOM), Andre Mischke (UU), Panos Christakoglou (FOM), Gert-Jan Nooren (FOM)

Nikhef collaboration

Nikhef is the National Institute for Subatomic Physics in the Netherlands, in which the Foundation for Fundamental Research on Matter, the University of Amsterdam, VU University Amsterdam, Radboud University Nijmegen and Utrecht University collaborate. Recently, two other Dutch universities, Leiden University and the University of Groningen, have expressed interest to join the Nikhef collaboration.

Nikhef coordinates and supports most activities in experimental particle and astroparticle physics in the Netherlands and in particular the Dutch CERN activities. Through Nikhef, the Dutch input to CERN Council, the highest managerial body of CERN, is prepared via the KNAW installed CERN Contact Committee. Nikhef coordinates the Dutch input to and presence in high-level strategic European committees such as: ECFA (European Committee for Future Accelerators); the quinquennial European Particle Physics Strategy event; and ApPEC (Astroparticle Physics European Consortium).

Nikhef coordinates the training and progress monitoring of its PhD students via the research school subatomic physics (OSAF). The central laboratory of the Nikhef consortium in Amsterdam avails of a state-of-the-art technical infrastructure and a staff of highly trained mechanical, electronics and computing engineers and technicians; a *sine qua non* for a successful participation in projects like experimentation at the Large Hadron Collider. Nikhef vigorously pursues valorization activities of its technical expertise via its P2IP (Particle Physics Inside Projects) subsidiary, a joint venture between Nikhef and an investment company. To date already two (ATLAS-related) technologies have led to start-up companies via this route.

4 Science Case

4.1 Particle Physics

The past century: the Standard Model of elementary particle physics

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 top-quark (1995) and the τ-neutrino (2000) at the Fermi Laboratory's Tevatron; and the recent discovery of the (or 'a'?) 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 and 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, and it connects the science of the infinitely large (astronomy) to the science of the infinitesimally small (particle physics).

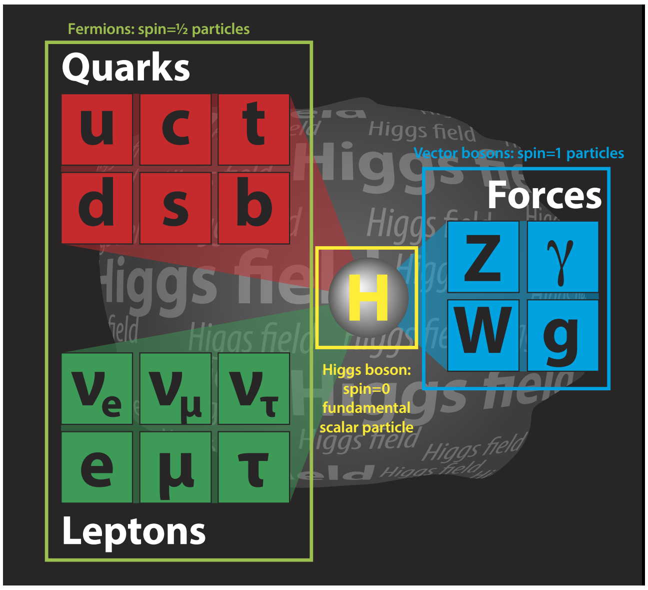


Figure 1. The particles of the Standard Model, including the Higgs boson.

The future: beyond the Standard Model of elementary particle physics

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. Couples the recently discovered Higgs particle indeed 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 its couplings to the massive W- and Z-bosons in accord with the mechanism of electroweak symmetry breaking as implemented in the Standard Model? Are its 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

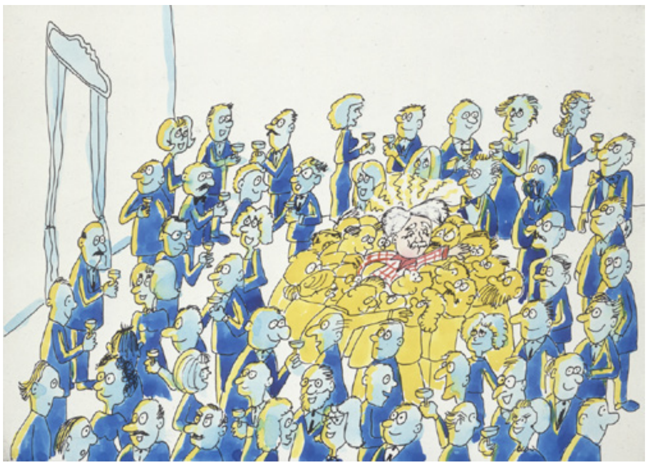


Figure 2. Cartoon explanation of the Higgs mechanism: a well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step. This increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field.

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 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.

CERN's Large Hadron Collider project is expected to yield the experimental evidence needed to clarify (some of) the just mentioned challenges and speculations in the coming years. A realization of any of the above speculations or the discovery of something entirely unexpected, will certainly revolutionize our view of the Universe in a way comparable to historic breakthroughs in the past such as: the discovery of neutral currents in 1973; the discovery of the charm-quark in 1974; or the announcement of neutrino oscillations in 1998. This is why the expectations of the Large Hadron Collider surpass those of any other (present and past) accelerator project and it is also understood that any future energy frontier accelerator project will only be decided upon, once the Large Hadron Collider has thoroughly explored the TeV scale.

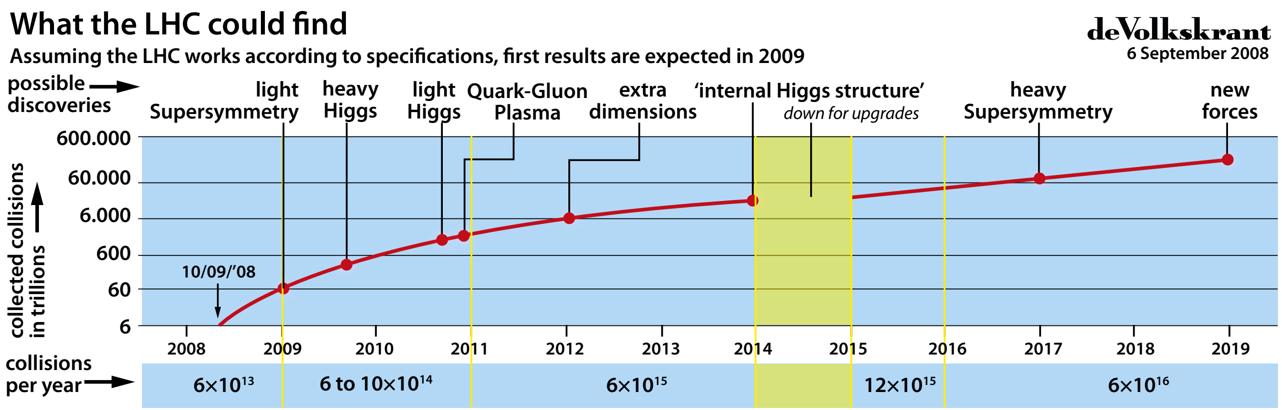


Figure 3. A rather optimistic overview of possible LHC discoveries by Martijn van Calmthout, the science editor of the Volkskrant, a national newspaper. In fact, the LHC experiments were delayed by more than a year due to a beam incident on 19 September 2008. A light Higgs particle was discovered in 2012; 1.5 years later than indicated in the figure.

4.2 Large Hadron Collider

The Large Hadron Collider (LHC, see cover illustration) at CERN (Geneva, Switzerland) became operational on 20 November 2009. Located in a 27 km circumference underground tunnel (the former LEP ring), it accelerates two beams of particles travelling in opposite directions to high energies, before they are made to collide with each other head-on. The start in November 2009 was the culmination of 14 months of hard work repairing, consolidating and commissioning the machine and preparing the beams after a fatal quench in one of the 1232 superconducting dipole bending magnets on 19 September 2008. Having learned the lessons from the incident, the LHC teams developed and installed mechanical and electronic systems designed to make the machine more robust and reliable. A new quench detection system was installed together with a new system to detect abnormally high resistances (high here stands for a couple of nΩ, *i.e.* a few 10^{-9} Ω). On 30 November 2009, the LHC became the World's highest energy particle accelerator when protons in each beam reached an energy of 1.18 TeV, surpassing the previous world record of 0.98 TeV established by the Tevatron collider at the Fermi Laboratory (Chicago, USA) in 2001.

Figure 4. Scientific and general interest magazines showed the stir after the announcement of the find of the Higgs particle (The Economist 7-7-2012) and acknowledged the importance when reviewing the breakthroughs of the year (Science 12-2012 [ref 1]).

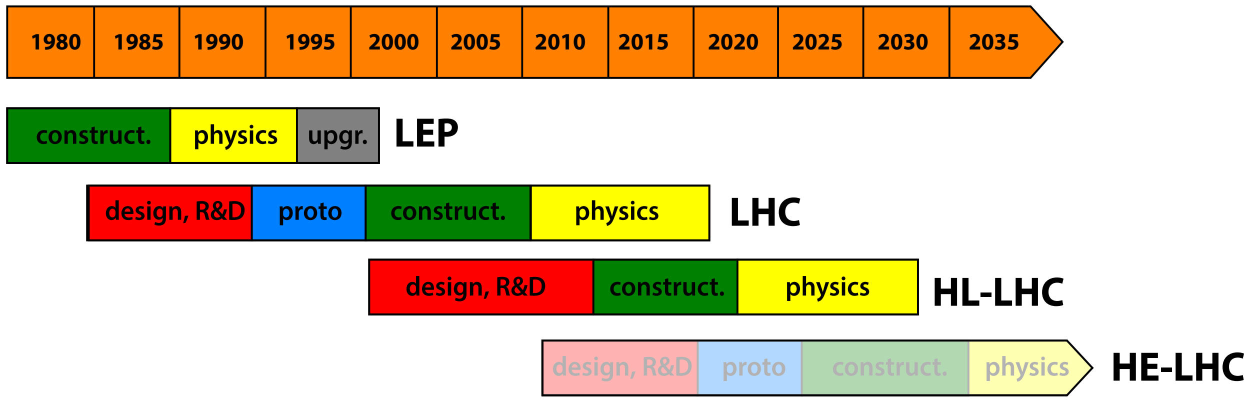


Figure 5. The super-exploitation of the CERN complex of injectors, LEP/LHC tunnel and infrastructure: timeline of the LHC machine and possible LHC upgrades. HL-LHC stands for High Luminosity LHC, and HE-LHC for High Energy LHC (not-approved yet).

In proton-proton mode the LHC delivers luminosity to all four main LHC experiments: the two general purpose experiments (ATLAS and CMS) and the experiment dedicated to study systems with b-quarks (LHCb) and the experiment designed to study heavy-ion interactions (ALICE). One month per year is set aside to operate the LHC in a dedicated mode colliding fully ionized lead atoms instead of protons to allow in particular the ALICE experiment to make very detailed measurements of the quark-gluon plasma.

The science programs of the three experiments with Dutch participation (ATLAS, LHCb and ALICE) outlined below each have their own focus and as a consequence operational constraints and characteristics. This is reflected in the accumulated integrated luminosity to date for each experiment as shown in Figure 6. A common feature of the processes studied by ATLAS (and CMS) is the presence of particles with high transverse energy. These are relatively easy to recognize, even in situations with many overlaying events (*i.e.* the occurrence of multiple, independent, proton-proton interactions when two proton bunches collide). 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 small number of overlaying events and therefore the luminosity at the LHCb interaction point is limited to about 0.4 $nb^{-1}s^{-1}$ (corresponding to an average of 1.7 proton-proton interactions when two proton bunches collide). This limit can be relaxed by a factor five after the upgrade of the LHCb detector in the 2017–2018 shutdown. ALICE is different again since the stringent requirements on tracking and particle identification impose the use of long drift times for some detectors (up to 80 μs), which prohibits operation with only 25 ns between subsequent proton bunch collisions. Instead only one pair of bunches collides in the ALICE interaction point thereby reducing the luminosity to about 10 $\mu b^{-1}s^{-1}$, thus effectively a factor 1000 below the peak LHC luminosity. Despite these differences, there are also common features between the experiments. Firstly, each experiment reduces the gigantic data volume via a step-wise real-time event selection process (*trigger*) to a manageable volume of typically a few hundred events per second corresponding to a few Gb/s data stream. Secondly this rate is distributed to the dedicated grid computing infrastructure of the Worldwide LHC Computing Grid for reconstruction, analysis and archive.

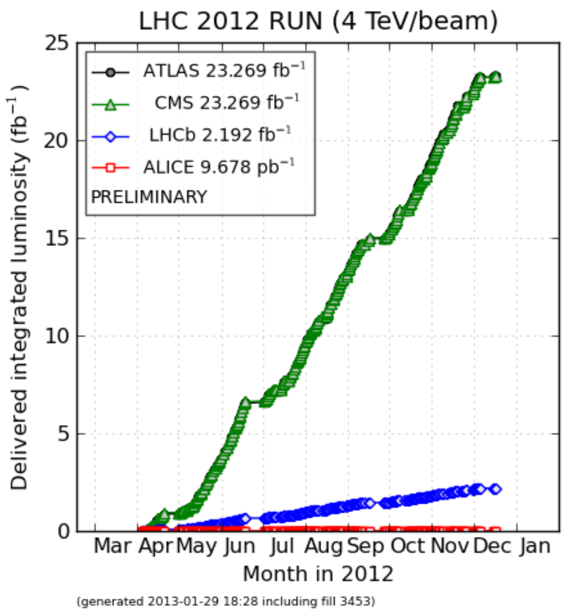


Figure 6. Luminosity during the 2012 run; for ATLAS and CMS the 2011 total luminosity was just 25% of that of 2012.

Awaiting the completion in the present shutdown of the safety precautions following the 2008 incident, the beam energy was limited to 3.5 TeV in 2010 and 2011 and 4 TeV in 2012. The number of colliding particle bunches will increase gradually to its design target of

	LHC Machine	Experiment upgrades
2011–2012	**Run 1:** 7-8 TeV centre-of-mass energy, luminosity ramping up to few nb^{-1}, 30 fb^{-1} delivered	
2013–2014	LHC shut-down to prepare machine for design *i.e.* 14 TeV centre-of-mass energy and nominal luminosity	ATLAS: phase-0 (new inner pixel detector layer) LHCb: consolidation ALICE: detector completion
2015–2017	**Run 2:** Ramp up luminosity to nominal (10 $nb^{-1}s^{-1}$); 50–100 fb^{-1}	
2018	Injector and LHC phase-1 upgrades to ultimate luminosity	ATLAS: phase-1 (muon chambers, trigger and data-acquisition) LHCb: full trigger upgrade, new vertex detector ALICE: new inner vertex system, TPC, data-acquisition
2019–2021	**Run 3:** Ramp-up luminosity to 2.2 × nominal, reaching 100 fb^{-1}/year; accumulate few hundred fb^{-1}	
2022–2023	LHC phase-2 upgrade: high-luminosity LHC. New focussing magnets and CRAB cavities for very high luminosity with levelling	ATLAS: phase-2 (new central tracker) ALICE: phase-2 (forward detectors)
2024–2036	**Run 4:** collect data until >3000 fb^{-1}	

Table 1. Provisional LHC schedule.

2808 bunches per beam when bunches will collide an astonishing 40,000,000 times per second, *i.e.* at 25 ns intervals. Meanwhile the nominal intensity per bunch has already been achieved.

On 14 February 2013, at 7:24 am, the shift crew in the CERN Control Centre extracted the beams from the Large Hadron Collider, bringing the machine's first three-year running period (Run 1) to a successful conclusion. The total integrated luminosity (a measure for the delivered number of particle collisions) for Run 1 was about 30 fb^{-1}. During Run 1, the general purpose experiments ATLAS (and CMS) collected almost the complete 30 fb^{-1}, whereas LHCb and ALICE, both operating at reduced intensity (as explained above), collected 3.4 fb^{-1} and 15.3 pb^{-1}, respectively. All three experiments collected data with near 100% efficiencies. During the last weeks of Run 1, the remarkable figure of 100 petabytes of data stored in the Worldwide LHC Computing Grid mass-storage systems was surpassed.

A long period of work on accelerator and detector systems has been planned for the 2013–2014 shutdown. For the experiments this implies repairs, improvements and extensions of various sub-detector systems. For the accelerator it means, apart from standard repairs and routine maintenance, the completion of the safety precautions such that the LHC bending magnets can safely be operated at full magnetic field strength. After these 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 $nb^{-1}s^{-1}$ (*i.e.* 50 fb^{-1} per year) in 2015 (Run 2). 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 (reaching about 20 $nb^{-1}s^{-1}$, *i.e.* about 100 fb^{-1} per year after the 2018 shutdown, Run 3) and/or to take advantage of the availability of new detector and computing/electronics technology to boost their discovery potential. After the last (2022–2023) shutdown the LHC is expected to run for about a decade (high-luminosity or HL-LHC operation, Run 4) to deliver at least 3000 fb^{-1}; *i.e.* a tenfold increase compared to the accumulated data set in the prior years. This vast data set is required to, for instance, map out the intricacies of the Higgs sector and in particular 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 set will extend the mass range for the discovery of new massive particles by about 30%. At that moment, after more than 20 years of LHC operation, the future 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?
Of course one has to keep in mind that, depending on Nature, we might discover Physics beyond the Standard Model much sooner or, if Nature is unkind, never.

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

Table 2. Detector related work of the Nikhef groups in the pre-datataking period.

If required, a doubling of the LHC beam energy by replacing all LHC bending magnets by more powerful ones might be considered. Alternatively, a large circumference proton-proton collider reaching up to 100 TeV in the centre-of-mass is also considered. R&D for high-field (>10 Tesla) superconducting magnets has already started. Alternatively, the focus could switch from proton to electron colliders, like the International Linear Collider (ILC) for 0.5–1 TeV centre-of-mass electron-positron annihilation experiments.

Figure 7. Peter Higgs (left) and Stan Bentvelsen (right) after prof. Higgs' colloquium at Nikhef.

4.3 Nikhef and the LHC

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 whereas 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 the LHCb experiment dedicated to the study of the minute matter-antimatter differences in systems with b-quarks. In 1994 Nikhef joined the ALICE experiment 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. As main proponent of the Dutch BiG Grid project (2006–2012), Nikhef has, in collaboration with SURFsara, setup one the 12 worldwide LHC Tier-1 in the Netherlands. This Tier-1 facility serves the ATLAS, LHCb and ALICE collaborations within the context of the Worldwide LHC Computing Grid (WLCG).

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); to allow complementary studies of quarks and gluons under extreme conditions (ALICE); and possibly to discover physics beyond the so-called Standard Model (ATLAS and LHCb), the successful theoretical framework accurately describing a wealth of experimental observations but *e.g.* falling short in explaining the nature of the mysterious dark matter in the Universe. 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. Already in 2011, Nikhef started the process to secure funding for both its contributions to the LHC detector upgrades as well as the continuation of the NL-Tier1 services by getting the LHC upgrade on the prestigious Dutch roadmap for large scale infrastructures.

Particle physics in general and the LHC project in particular are curiosity driven research activities. As such they attract 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. Nikhef has also taken the initiative to host a CERN Business Innovation Center (BIC) at Science Park Amsterdam: the second in Europe. A CERN BIC aims to market technology at CERN by providing an attractive environment of low cost office and lab space, entry to venture capital and legal and business development expertise. Following the last (2012) evaluation of Nikhef, Nikhef decided to explicitly include knowledge and technology transfer to third parties in its mission.

> *The mission of the National Institute for Subatomic Physics Nikhef is to study the interactions and structure of all elementary particles and fields at the smallest distance scale and the highest attainable energy.*
> *Two complementary approaches are followed:*
> **Accelerator-based particle physics** – *Studying interactions in particle collision processes at particle accelerators, in particular at CERN;*
> **Astroparticle physics** – *Studying interactions of particles and radiation emanating from the Universe.*
> *Nikhef coordinates and leads the Dutch experimental activities in these fields. The research at Nikhef relies on the development of innovative technologies. The knowledge and technology transfer to third parties, i.e., industry, civil society and general public, is an integral part of Nikhef's mission.*
>
> *Nikhef mission statement*

This proposal, *'LHC physics – the Dutch participation'*, aims to primarily secure the funding for temporary scientific staff (PhD students and postdocs). This is vital for a continued participation of the Netherlands in experimental particle physics in general and in CERN's Large Hadron Collider project in particular.

4.4 The European Particle Physics Strategy and the LHC

The CERN convention, which was drafted nearly 60 years ago, foresaw the CERN organization to act both as coordinator of particle physics in Europe as well as to operate one or more accelerator laboratories in Europe. The nowadays often very long lead times to prepare and construct particle physics facilities and experiments, combined with the ever increasing costs for these activities, demand an European strategy for this field. Therefore CERN Council started the so-called *European Strategy for Particle Physics* process in 2005 to prioritize the various scientific opportunities. Such a process includes an open symposium to collect input from the entire community; in depth scrutiny of the different options by dedicated working groups composed of experts; consultation with adjacent fields of research, notably astroparticle and nuclear physics; and discussions with representatives from the Americas and Asia. The *European Strategy for Particle Physics* itself is drafted during a dedicated week-long meeting by representatives of the CERN member states. This strategy comprises a limited number (about 20) of concise action statements. These address not only scientific issues but also topics such as the organizational and societal relevance of particle physic research. This draft strategy is presented to CERN Council for approval. The strategy is, possibly after some iterations, approved during a dedicated session of CERN Council.

Figure 8. European Strategy Symposium 2012 in Kraków.

The first *European Strategy for Particle Physics* was adopted by CERN Council in July 2006 during a dedicated session in Lisbon[1]. It contained 17 strategy statements. The highest scientific priority was the full exploitation of the Large Hadron Collider (LHC) project, directly followed by accelerator R&D projects in view of the luminosity and energy upgrades of the LHC, linear electron-positron colliders and intense neutrino-beam facilities.

> *"The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance. A subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity 2015."*
>
> *2006 European Particle Physics Strategy*

1 http://council.web.cern.ch/council/en/EuropeanStrategy/ESStatement.pdf , 14 July 2006.

Already in 2006, CERN Council adopted the strategy with an understanding that it be brought up-to-date at regular intervals of typically five years. The first update has been prepared in January 2013, following the same process as in 2005–2006, and has recently been approved by CERN Council. It was formally adopted by a dedicated session of CERN Council and high-ranking EU representatives in Brussels on 30 May 2013. The process was postponed for two years in order to include first results of the LHC experiments taking data at 7–8 TeV centre-of mass energies. As a result, the new strategy takes into account the discovery of the (or 'a'?) Higgs particle. It also pays tribute to the fact that the hitherto unknown third mixing angle θ_{13} in the neutrino mass-matrix has recently been measured by various experiments to be such that studies of CP-violation in the leptonic sector becomes feasible using (intense) neutrino-bean facilities. Both the status of the Higgs particle (*does it exist or not?*) and the magnitude of θ_{13} (*is it sufficiently large to allow CP-studies in the leptonic sector?*), were already identified in the 2006 strategy statement as crucial information required for an update of the strategy.

As in the 2006 strategy statement, also the 2013 strategy statement lists the LHC as the first and thereby highest priority project:

> *"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*

4.5 ATLAS: Exploring the TeV Scale

The ATLAS collaboration was established in 1991 with Nikhef as a founding member, and consists of about 3000 physicists (including 1000 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, with 90 million electronic channels, 25 meters high, 44 meters long and with a weight of 7,000 tons[ref 4]. In 2012, a major success was reached by the discovery of a new particle, compatible with the long-sought Higgs boson[ref 1]. Presently Nikhef is one of the 10 largest groups within ATLAS.

Figure 9. Technicians at work inside the ATLAS detector.

A. Scientific objectives and focus

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 breaking of the symmetry between weak and electromagnetic interactions proceeds through the mechanism described by Higgs, Brout and Englert[ref 3], leading to the prediction of the existence of a new scalar particle, the Higgs boson. Before the LHC started operation, this theory lacked experimental verification. ATLAS and CMS have now found a new particle that is consistent with being a Higgs boson[ref 2]. The further clarification of electroweak symmetry breaking involves a study of the nature of the new particle, in particular a measurement of its couplings to the other Standard Model particles and to itself, in order to investigate whether the new particle behaves like a Standard Model Higgs boson, or whether New Physics is at play. Models of New Physics also may predict the existence of multiple Higgs bosons;
- 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 a 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, hinting –if they exist– to supersymmetry or other theories, such as: new heavy gauge bosons; Kaluza-Klein states predicted in theories with more than four space-time dimensions; and fourth generation 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.

B. Science challenges

The future scientific challenges for ATLAS are closely related to the results achieved in Run 1 (2009–2012). Immediately from the start of the LHC run 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 constructed by Nikhef operate well, with a minimum number of defective channels, and also the alignment system and the detector-control system operate as designed. The silicon strip detector operates with high efficiency, and studies of dark current and noise show that radiation damage to the sensors 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.

In 2010 and 2011, ATLAS collected a data sample corresponding to a luminosity of 5 fb^{-1} at a centre-of-mass energy $\sqrt{s}$=7 TeV, and in 2012 a much larger data sample of 20 fb^{-1} was collected at $\sqrt{s}$=8 TeV. To date, ATLAS has published over 250 scientific papers and approximately 500 conference contributions, on topics ranging from the discovery of a Higgs boson, precision measurements of top quark production and weak gauge boson production, tests of quantumchromodynamics, bottom-quark physics, to searches for physics beyond the Standard Model. This demonstrates not only that the ATLAS detector functions well, but also that the complete chain of reconstruc-

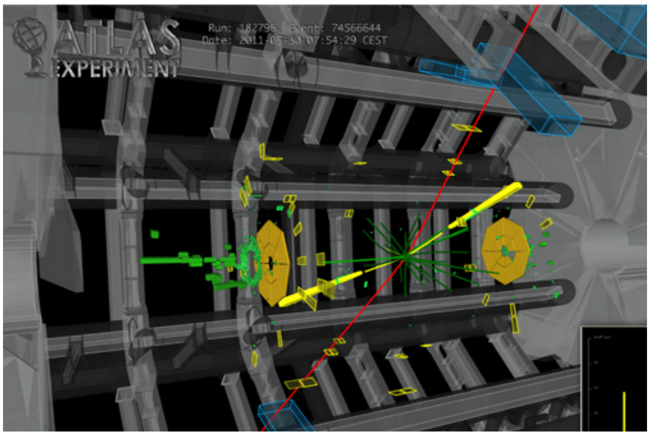


Figure 10. A display of a Higgs boson candidate event recorded by ATLAS. The Higgs boson decays into two Z bosons, which decay in a pair of muons (red) and electrons (yellow).

tion, simulation and analysis software runs smoothly and effectively on the worldwide LHC computing grid (WLCG).

The Dutch ATLAS group has concentrated in Run 1 on three physics analysis themes: Top quark physics, Higgs physics, and searches for new phenomena beyond the Standard Model, in particular supersymmetry. We have played a major role in the discovery of a Higgs boson, and in placing significant constraints on supersymmetry. We intend to remain focused on these topics in Run 2, and Higgs physics and physics beyond the Standard Model form projects 1 and 2, respectively, as described below.

The discovery of a Higgs boson, or searches for New Physics, would not have been possible without detailed understanding of the Standard Model background at 7 and 8 TeV energies. Since those energies have never been probed before, it is in fact ATLAS and CMS themselves that have probed and tested the Standard Model in this new regime. The Nikhef ATLAS group has played an significant role from the start in the measurement of inclusive charged particle production, motivated by our construction of one end-cap of the silicon strip detector, as well as inclusive muon production, motivated by our construction of large barrel muon chambers, where we have systematically investigated the sources of muons as a function of momentum and rapidity. From the start of ATLAS, Nikhef has been involved in muon reconstruction software. Our main attention, however, has been focused on top quark production, both in terms of first measurements of cross sections of top quark pair production[ref 6], and first evidence for single top quark production in association with a W boson. We have had leading roles in these analyses, which also include detailed studies of the main backgrounds to top production originating from electroweak gauge boson production. The Nikhef group has also made a measurement of top quark production in the top quark decay mode to a tau lepton. Within the statistics of the samples collected to far, the Standard Model theory is well able to describe the ATLAS data at 7 and 8 TeV. This is shown in Figure 11.

The goal of Run 2 of the LHC, which is foreseen between 2015 and 2017, is to provide an integrated luminosity between 50 and 100 fb^{-1} at a centre-of-mass energy of at least 13 TeV, possibly to be upgraded to the ultimate energy of 14 TeV. The instantaneous luminosity delivered to ATLAS will be of order of the LHC design luminosity of 10 $nb^{-1}s^{-1}$, implying 25–50 (depending on the time between bunches) interactions per bunch crossing. After a second shutdown around 2018, a further LHC run between 2019 and 2021 could deliver a total of 300–500 fb^{-1} of data at 13 or 14 TeV. Although the conditions will be challenging, such a large data sample will enable ATLAS to exploit the science case for which the LHC was designed.

The total physics analysis activities of the ATLAS collaboration are extensive, and comprise many topics. Public results have been published on hundreds of analyses, which are organized in ATLAS in physics groups: (non-Higgs) Standard Model physics, top quark physics, bottom quark physics, heavy ion collision physics, Higgs physics, searches for supersymmetry, and searches for (non-supersymmetric) exotic phenomena. The Nikhef ATLAS group has made a choice to focus on the projects listed below, which represent for us the most pressing scientific challenges of ATLAS in Run 2. Following the discovery of a Higgs boson and the new questions that arise, we allocate most manpower to project 1, while keeping enough 'mass' in project 2: in order to remain at the front of physics analysis in ATLAS a minimum group size is needed.

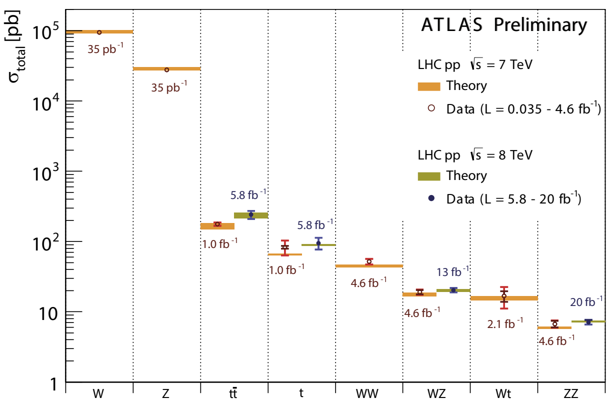


Figure 11. Summary of cross section measurements of important Standard Model processes in the new energy domain of the LHC in Run 1.

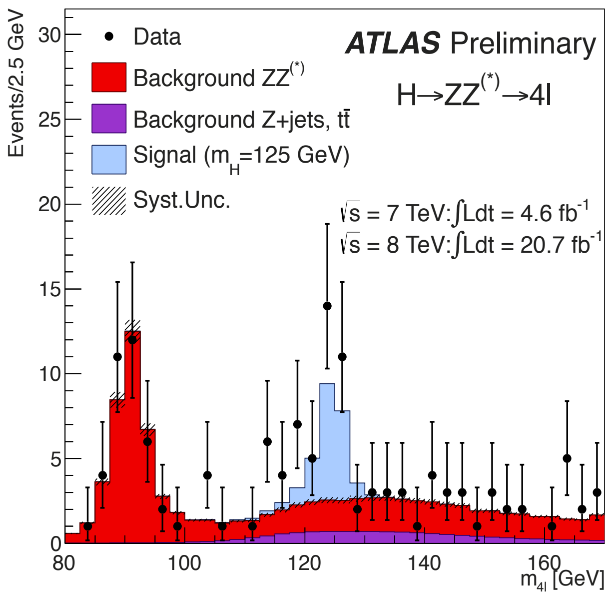
Furthermore, there are detector-hardware-related technological challenges, and the effort we will invest in solving those challenges (in project 3) supports projects 1 and 2, but also prepares ATLAS for the future HL-LHC.

The Nikhef ATLAS group consists of physicists at the Radboud University Nijmegen/Nikhef, and physicists at Nikhef Amsterdam, either employed by the University of Amsterdam or by FOM. At Nikhef Amsterdam, the FOM and UvA groups are fully integrated. The groups in Amsterdam and Nijmegen cooperate closely, bringing in their own expertise. Within the projects, the group members from both locations meet on a weekly or bi-weekly basis, either in person or using videoconferencing, and including also the people based at CERN. Furthermore, there is a weekly overall Nikhef ATLAS group meeting.

We discuss the science case for the activities of the Dutch groups in Run 2 below. Our focus is on detailed study of electroweak symmetry breaking, and on searches for new phenomena beyond the Standard Model. Our expertise in top-quark physics gained in Run 1 will be used in both these topics: in studies of Higgs production associated with top quarks, and in searches for new top quark partners, where top quark production is the major background. The technological challenges are discussed after the physics analysis projects.

Project 1. Precision study of electroweak symmetry breaking and the Higgs boson
At the LHC the dominant production mode of the Higgs boson is gluon-gluon fusion. Vector boson fusion and associated production with gauge bosons or top quarks have cross sections that are an order of magnitude smaller. The Higgs boson is short-lived and decays to a number of final states or channels at a rate that is proportional to its coupling to the particles in this channel. For the discovery the three relevant decays channels are those into a pair of W-bosons (WW), a pair of Z-bosons (ZZ) and a pair of photons (γγ). With increased statistics other decay channels may become accessible. Figure 10 shows a recorded Higgs candidate event in the H→ZZ→eeμμ decay mode, Figure 12 shows the invariant mass of final state particles, exhibiting a peak around 126 GeV.

The Dutch ATLAS group was one of the driving forces in the H→WW channel. We also made a number of important contributions to the H→ZZ channel, in particular by improving the muon identification efficiency using both muon chambers and the calorimeter and optimizing the event selection for maximal discovery potential. In addition we played a central role in the statistical combination of all Higgs channels with a Nikhef scientist (W. Verkerke) being the main author of the statistical toolkit (RooFit) used in the process. The 'workspace' concept of RooFit, developed especially for LHC Higgs combinations, has played a key role in the rapid combination of channels for the Higgs discovery, and has shaped and simplified the design of statistical combination procedures.



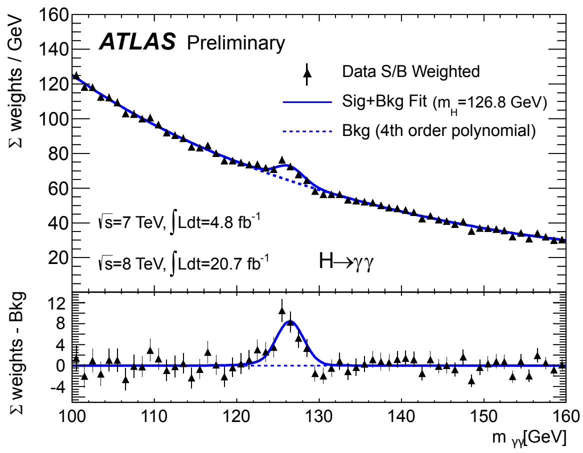


Figure 12. Invariant mass of 4 leptons (left) or 2 photons (right) in the Run 1 ATLAS data, exhibiting a peak that indicates the mass of the Higgs boson around 126 GeV.

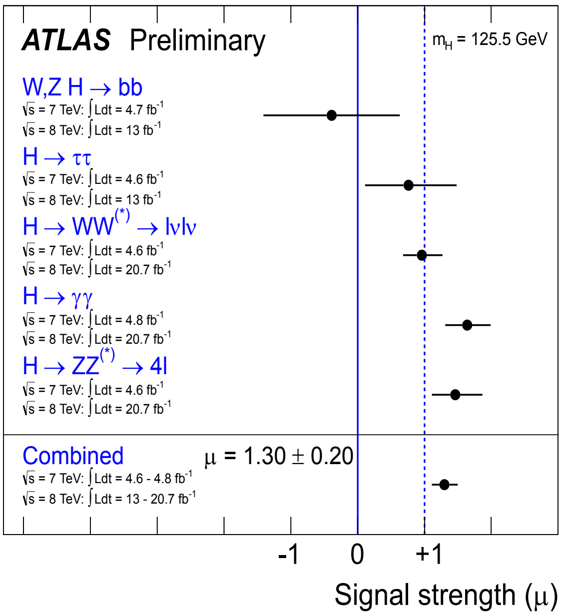


Figure 13. Measured Higgs boson signal strength, normalised to the Standard Model prediction, in Run 1 ATLAS data in various Higgs decay channels.

Preliminary analyses of angular correlations of the decay products with the full 2012 data set provide strong evidence that the quantum numbers of the new particle are indeed compatible with those of a Standard Model Higgs boson. Our group has contributed to this analysis in both the WW and ZZ channels. The ATLAS collaboration have also seen evidence for the vector-boson fusion production process of the Higgs boson, with Nikhef as a leading partner in the analysis.

With the discovery of the new boson the focus has shifted to understanding the nature of electroweak symmetry breaking. Some questions that we seek to answer are:

- What are the quantum numbers of the new boson?
- Is this a fundamental particle or is it composite?
- Is this a single particle or an admixture with another scalar?
- Are there more similar scalars as predicted by *e.g.* supersymmetry?

The key to these questions lies in the couplings of the Higgs boson to the other particles in the Standard Model. The current data provides relatively weak constraints on the couplings to W and Z bosons and the coupling to top quarks. With the Run 2 data set with 10 times more data we will be able to make a much more precise measurement of these couplings for the WW and ZZ channel and search for deviations from the Standard Model. With the increased statistics we also become sensitive to possible heavier sequential Higgs boson that decay in these channels, and to Higgs decays to pairs of bottom quarks and to pairs of tau leptons. Figure 14 shows the sensitivity expected by ATLAS from simulations [ref 7].

Of particular interest is the study of Higgs production in association with a pair of top quarks. This gives a direct measurement of the top-Higgs coupling. This coupling is the dominant contribution to the gluon-gluon fusion process and contributes to the Higgs decay into two photons, but in both cases new heavy particles can modify the rate. A difference between the direct measurement and the indirect determination would be a smoking gun for New Physics. In this measurement, we will benefit from our expertise in top physics. Another interesting channel is the decay into two muons because it would demonstrate the Higgs mechanism at work at a mass scale which is three orders of magnitude smaller. It is a clean decay mode and the final state has significant overlap with the vector-boson fusion WW analysis.

One other feature of a Higgs boson is that it could damp the rise of the cross section of vector-boson scattering in the longitudinal mode, which would otherwise violate unitarity. It is important to verify this experimentally. Alternative theories encompass TeV scale resonances. The projected data set of Run 2 should be sensitive to vector resonances with a mass above 800 GeV. The final state of this analysis is almost identical to that of the vector-boson fusion Higgs search and we expect strong synergy with our analysis effort in this channel. Since top quarks are the dominant background for this analysis we will also benefit from our top quark expertise.

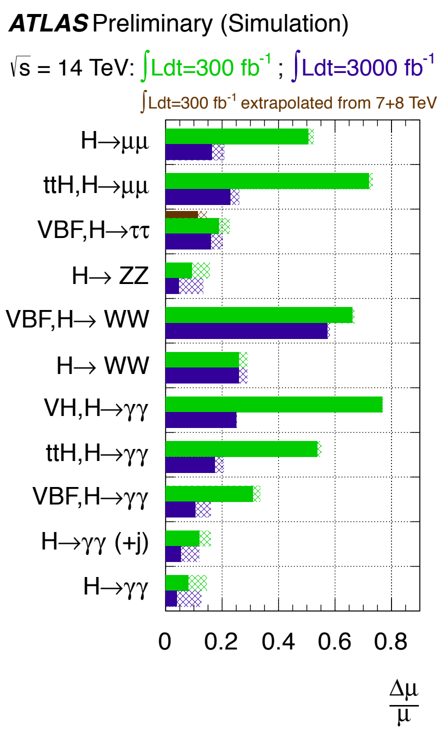


Figure 14. The expected uncertainty, from simulations, on the Higgs signal strength, derived from analyses of 300 fb⁻¹ (green) or 3000 fb⁻¹ (blue) of data, to be collected by ATLAS at 14 TeV.

The following physicists of the Dutch ATLAS group will be part of project 1: S. Bentvelsen (UvA), G.J. Bobbink (FOM), P. Ferrari (FOM), F. Filthaut (RU), N. de Groot (RU), P. Kluit (FOM), W. Verkerke (FOM),

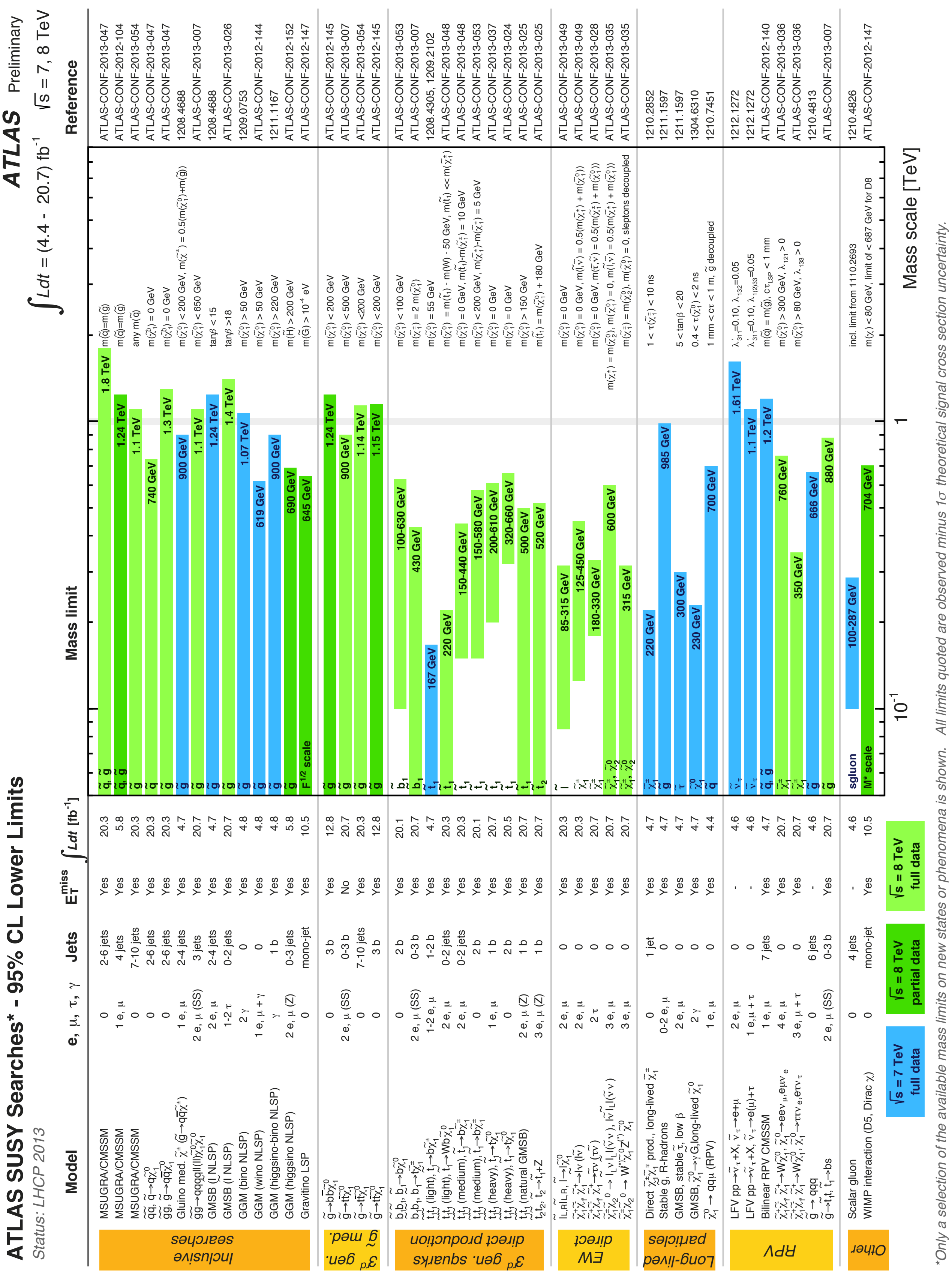


Figure 15. A summary of limits and constraints on the masses of supersymmetric particles, resulting from analyses of ATLAS data collected in Run 1.

M. Vreeswijk (UvA), and I. van Vulpen (UvA). For this project we request nine PhD students and three postdocs. The proposed PhD student projects are listed in Table 3, and focus on the determination of the most important Higgs boson properties: mass, production mechanism, couplings to vector bosons, couplings to leptons, couplings to heavy quarks, unitarity restoration and the possible existence of more than one Higgs boson. Together, these projects fully test the predictions of the Higgs mechanism of electroweak symmetry breaking, as far as possible with the luminosity expected in Run 2 of the LHC.

The projects connect with Nikhef expertise as follows:

- Precision measurement of production and decay of the newly discovered Higgs particle in multiple channels: WW, ZZ, bb, di-lepton, and ttH. Nikhef expertise: muon reconstruction, b-quark tagging, H→ZZ and H→WW analysis, tau ID, analyses of associated production of H with a vector boson and with top quarks, spin and parity determination in WW and ZZ channels.
- Statistical and systematic issues in Higgs properties combination fits. Nikhef expertise: RooFit and RooStats software, many-dimensional fitting techniques.
- Study of WW scattering at high energy. Nikhef expertise: WW selection, Monte Carlo techniques for non-Standard Model WW scattering: the CAMGEN program.

In order to carry out the proposed program, expertise from the theory community, and in particular discussions with and support from the phenomenology community, are crucial. At Nikhef and in Nijmegen, we plan close collaboration with E. Laenen, W. Beenakker, and R. Kleiss.

Project 2. Searches for New Physics using the high energy and high luminosity of the LHC

Although the full power of the LHC is yet to be unleashed, even the LHC at near half power (8 TeV) is a major step beyond previous accelerators such as the Tevatron at Fermilab, and the collected data sample provides fertile ground for searches for New Physics. These analyses include a large variety of searches for supersymmetric particles (more than 50 papers published), extra space-time dimensions, contact interactions, new quarks and new gauge bosons. Although no evidence for new phenomena was found so far, limits on New Physics have been set that far surpass earlier results, and which form the tightest constraints on New Physics to date [ref 5]. As an example, Figure 15 shows a summary of ATLAS limits on masses of supersymmetric particles.

The Nikhef ATLAS group has focused on searches for supersymmetric particles, in particular inclusive searches for squarks and gluinos, and dedicated searches for third generation squarks, motivated by naturalness arguments. Furthermore, we have analysed multi-lepton final states and we search for lepton-flavour violating processes. A unique contribution is a general search for New Physics by comparing event counts in a very large number of topologies to the Standard Model expectation. Of course with less than one percent of the ultimate LHC data sample analysed, it is too early to make firm conclusions.

A crucial difference between the LHC of Run 1 and the LHC in 2015 and after is the LHC beam energy. The interventions performed on the LHC magnets in 2013 and 2014 will allow for an increase in beam energy to at least 6.5 TeV, and possibly 7 TeV later, leading to a centre-of-mass energy of 13 (14) TeV. Unleashing the full energy of the LHC is very important for searches for new massive particles. The ratio of parton luminosities between beam energies of 7 TeV and 4 TeV is about a factor 100 for gluon-gluon induced interactions at a gluon-gluon centre-of-mass energy of 2 TeV. In other words, for such interactions, each inverse fb of data collected at 14 TeV is worth 100 inverse fb at 8 TeV. Thus, the LHC after 2015 is exploring new territory after only a few months of data, with sensitivities that far outpace the ones at 8 TeV. On top of this, the integrated luminosity to be delivered before 2022 is 10–20 times larger than the one of Run 1. This large luminosity will also enable precision studies that require a large event sample, and where deviations from the Standard Model prediction are searched for, possibly indicating New Physics.

A priority for ATLAS is the search for new particles predicted by supersymmetry. Supersymmetry is a very powerful and deep symmetry relating space-time symmetries with internal symmetries. If supersymmetry exists, however, it must be broken, and the breaking mechanism is model-dependent. Supersymmetric particles with masses at the TeV scale are motivated by the fact that the lightest, stable supersymmetric particle would be an excellent candidate for dark matter, by the possibility of gauge coupling unification in one point, and in particular by 'naturalness' and the hierarchy problem. With 300 fb^{-1} of data, we expect to be sensitive to the discovery of squarks with masses up to 2.3 TeV, independent of the gluino mass, and of gluinos with masses up to 2 TeV, for all squark masses, as shown in Figure 16[ref 7]. We expect to be able to discover top squarks with masses up to 1 TeV, covering a major part of the phase space where top squarks are playing a role in the solution of the hierarchy problem. We are sensitive to weak gauginos with masses up to approximately 500 GeV in realistic scenarios where the gauginos decay to the lightest neutralino and W/Z bosons.

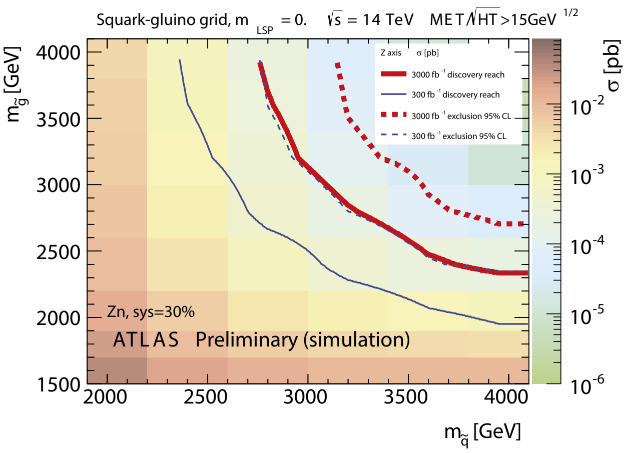


Figure 16. Expected sensitivity, from simulations, for supersymmetric quarks (squarks) and gluons (gluinos), for 300 fb^{-1} (blue) and 3000 fb^{-1} (red) at 14 TeV.

Standard Model processes can produce final states that mimic signatures of New Physics, and thus form a background noise to the searches for a New Physics signal. A major background noise to searches for supersymmetry, and other New Physics, is formed by top quark pair production and single top quark production. Detailed studies of these processes are very interesting, since they are themselves sensitive to New Physics, and because the modelling of top quark production by simulation is currently a high-priority line of research in the theory/phenomenology community. New physics in top quark production and decay can be studied by accurate measurements of differential cross sections, the asymmetry between top and anti-top production, spin correlations, and W polarization in top decays. A study of the invariant mass of the top quark pair system could show new resonances. Rare top quark decays and flavour-changing neutral currents could be a sign of the contributions of New Physics in loops.

Within the Standard Model, the conservation of lepton flavour holds, but is considered an accidental symmetry. Neutrino oscillations violate lepton flavour conservation, and the study of lepton flavour violation is in fact a portal towards the study of New Physics. Some models of New Physics predict lepton flavour violation at a rate that exceeds the Standard Model prediction (including neutrino oscillation effects) significantly, and which may be measured at the LHC, due to the very high rate of lepton production. We focus on lepton-flavour violating Z and tau lepton decays.

The LHC provides a unique window to New Physics searches, but the New Physics may be different from the predictions of our models. In order not to miss the LHC opportunity, we foresee to search for New Physics in a very generic, model-independent way, by a systematic and rigorous comparison of data in a large number of final states and topologies to the Standard Model expectation. The following physicists of the Dutch ATLAS group participate in project 2: D. Berge (UvA), S. Caron (RU), O. Igonkina (FOM), P. de Jong (UvA).

For this project we request seven PhD students and three postdocs. The proposed PhD projects are listed in Table 3. The Dutch ATLAS group concentrates on searches for supersymmetry (inclusively for squarks and gluinos, and with dedicated searches for top squarks and gauginos, motivated by naturalness arguments), and in searches for lepton flavour violation. Furthermore we want to study non-Standard Model production and decay modes of the Higgs boson, and we want to do a general, model-independent search for new phenomena at the LHC in Run 2. The projects are chosen for their relevance in testing models of physics beyond the Standard Model, and because of our expertise.

Nikhef expertise is represented in the projects as follows:

- Searches for new particles, in particular those predicted by supersymmetry, and non-standard Higgs production. Nikhef expertise: inclusive searches for squarks and gluinos, searches for third generation squarks, searches in multi-lepton final states, searches for mono-jet final states, expertise in b-tagging and trigger.
- Searches for lepton flavour violation. Nikhef expertise: searches in multi-lepton final states, tau identification, trigger.
- A model-independent search for New Physics. Nikhef expertise: model-independent search in ATLAS Run 1, trigger.

Also for project 2, theory support at Nikhef (E. Laenen) and RU (W. Beenakker) is important. Furthermore, we cooperate with the GRAPPA (Gravitation and Astroparticle Physics) group at the UvA (G. Bertone, and D. Berge are GRAPPA members), and we are in contact with members of IMAPP (Institute for Mathematics, Astrophysics and Particle Physics) at the RU.

C. Technology challenges

The increasing luminosity and energy of the LHC provide a challenge to ATLAS. In 2013 and 2014, ATLAS intends to complete the installation of the muon chambers, replace a part of the beam-pipe in the calorimeter end-cap region, upgrade the trigger/DAQ system for higher luminosities, make modifications to the inner detector cooling system, and replace elements of the optical read-out system in pixel- and SCT detector. The pixel detector will be taken out of ATLAS and brought to the surface for repair, and be re-installed in 2014. This will also facilitate the main foreseen upgrade of ATLAS in Phase-0, which is the installation of the IBL, or insertable B-layer. To maintain b-tagging capabilities when the inner layer of the current pixel detector will be affected by the accumulated radiation dose, the current beam-pipe will be replaced by a smaller-diameter beampipe, with silicon pixel sensors mounted on it. Nikhef is involved in the design and characterization of the IBL pixel read-out chip, and in the detector cooling system. Profiting from the ever smaller feature size in microelectronics, Nikhef designed important parts of the pixel-chip electronics with enhanced intelligence per pixel. Nikhef is a leading institute for research on thermal management of vertex detectors, and for the IBL we are responsible, together with CERN, for the design and construction of a 3 kW CO_2 cooling plant, to be delivered during 2013. In the trigger system, ATLAS will upgrade Level 1 with a topological trigger that will enable smarter trigger logic at early trigger stages. Nikhef is involved in electronics that will interface muon trigger signals with the new topological trigger, so that this new trigger logic includes the muon system.

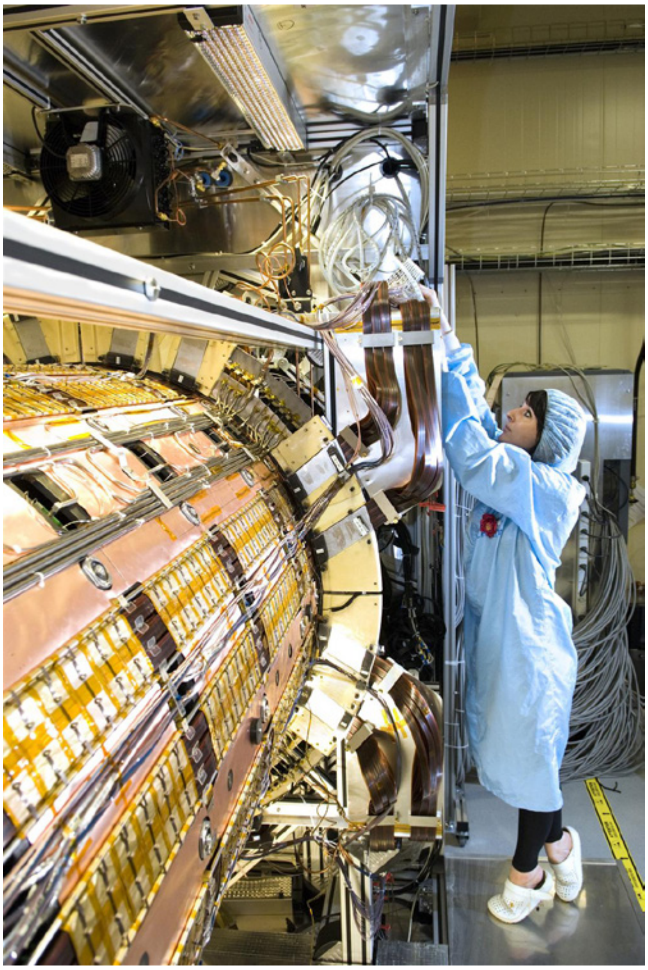


Figure 17. Nikhef PhD student working on the ATLAS semiconductor tracker (SCT).

Around 2018, ATLAS foresees to upgrade a number of detector elements, in order to be able to sustain the higher data rates and to improve the trigger for LHC luminosities above the design value of 10 $nb^{-1}s^{-1}$. For the muon system, the inner forward wheels ('small wheels') will be replaced by new chambers combining Micromegas and TGC technology. The new system will be important in keeping Level-1 trigger rates low, and in sharpening the trigger thresholds. Nikhef is interested in the read-out of this new system, which will be a prototype for a later Phase-2 (HL-LHC) system. Further elements of the Phase-1 upgrade include new calorimeter read-out and trigger electronics, and a fast track trigger. Preparations for the 2018 upgrade have already begun: letters-of-intent have been submitted to and approved by the CERN-LHCC, and technical design reports are being prepared [ref 7].

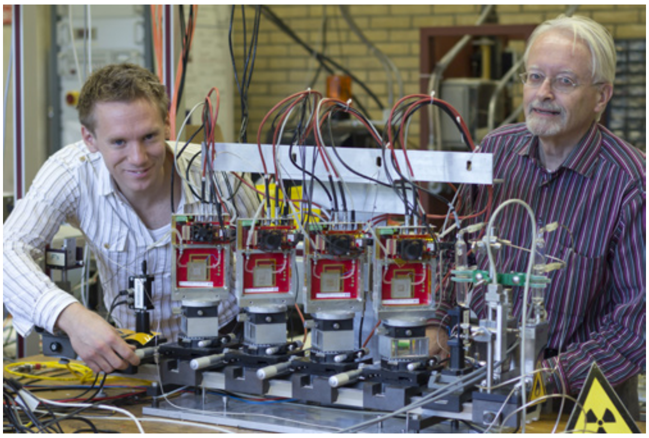


Figure 18. Development of new technology at Nikhef for a future ATLAS inner tracker.

By 2021, ATLAS could have collected some 300–500 fb^{-1} of data. Any further exploitation of the LHC would need an order of magnitude more luminosity, and therefore the goal of the High-Luminosity LHC (HL-LHC) proposal is to provide 3000 fb^{-1} before 2030, with an instantaneous luminosity at or above 50 $nb^{-1}s^{-1}$. The physics motivation lies mainly in measurements that are statistically limited. These include Higgs couplings to gauge bosons and fermions, Higgs self-couplings, rare Higgs, t- and b-quark decays and WW scattering. A tenfold luminosity increase provides a New Physics discovery potential that is typically 30% larger in terms of new particle mass reach than at the nominal LHC.

An HL-LHC will require a significant upgrade of ATLAS. The inner detector must be replaced by a new all-silicon detector that is more radiation hard, and finer segmented, since the current pixel and strip detectors will not be able to survive the high radiation dose associated with the HL-LHC, and the current straw tune detector will have a too high occupancy. Calorimeter and muon read-out electronics, and the data acquisition system, must be upgraded.

Although the HL-LHC itself falls outside the scope of this programme proposal, we must prepare ourselves for the HL-LHC already well before 2022 in the form of research and design studies, if we want to remain at the forefront in ATLAS. There are interesting technical challenges to solve. At Nikhef we are focusing on the following projects:

- Scaling up of the IBL cooling project for a much larger Phase-2 inner detector cooling system using CO_2 cooling technology;
- Studies for a new end-cap silicon strip detector with a petal design. We are investigating material choices, thermal behaviour, assembly methods and integration, and support structures. If an ATLAS Phase-2 upgrade is approved, we are interested in the construction of a significant part of the new inner detector at Nikhef during the period 2018–2022;
- For trigger and data-acquisition upgrades we are studying new trigger strategies, improved high-level trigger architecture, and data flow optimization. We are also interested in studying a new Level-1 track trigger, possibly involving innovative GridPix MEMS technology.

We will further investigate which parts of the muon chamber hardware and read-out electronics will need to be upgraded in order to cope with the increased read-out rate.

Project 3. Detector upgrade for higher luminosities

Project 3 encompasses studies and work related to detector consolidation and detector upgrade for higher luminosities, as discussed above under technological challenges. The following physicists of the Dutch ATLAS group are involved in project 3: N. Hessey (FOM), A. König (RU), J. Vermeulen (UvA). Part-time: S. Bentvelsen (UvA), G.-J. Bobbink (FOM), D. Berge (UvA), S. Caron (RU), O. Igonkina (FOM), P. de Jong (UvA), P. Kluit (FOM), E. Koffeman (FOM & UvA).

It is foreseen that manpower for these projects is mainly delivered by staff physicists and by engineers and technicians at Nikhef, as well as by the PhD students and postdocs associated to projects 1 and 2, who will be required to spend a fraction of their time on technical work for project 3. However, for the design of the new inner detector and the construction of one end-cap, we request two dedicated PhD students; with proposed theses topics as listed in Table 3.

Nikhef expertise is reflected in the following subprojects:

- Trigger/DAQ. Development of new trigger and data acquisition strategies, simulation of data flows, design of new architecture.
- Muon chambers. Read-out architecture for the new small wheels, which will also serve as template for a phase-2 upgrade read-out architecture. Maintenance of alignment and slow-control systems.
- Inner detector. Design of a new all-silicon tracker system for the HL-LHC, and construction of one strip tracker end-cap. Design of a cooling system for the new tracker, design of a read-out chip.

D. Theses projects

Higgs PhD theses

- Precision measurement of Higgs boson mass and cross section from H→llll decays
- Observation of the vector boson fusion production mechanism in the H→WW channel
- Observation of H→bb decays and direct evidence for the Hb coupling
- Observation of H→ττ and evidence for Higgs couplings to leptons
- Observation of ttH associated production and measurement of the tH coupling
- Search for the decay of the Higgs boson in the μμ final state
- Precision determination of Higgs boson couplings by combined fits to multiple final states
- Is there room for another Higgs boson? A search for other Higgs-like particles
- Study of WW scattering and unitarity restoration at $\sqrt{s}$ = 13/14 TeV

Beyond the Standard Model PhD theses

- Inclusive searches for squarks and gluinos at the LHC
- A search for the supersymmetric partner of the top quark
- Searches for dark matter particles in mono-jet final states and through invisible decays of the Higgs boson
- Searches for gauginos and other New Physics in multilepton final states
- Searches for lepton flavour violation in τ lepton decays at the LHC
- A search for non-Standard Model sources of Higgs boson production
- A model-independent search of new phenomena at the LHC

Inner Tracker upgrade PhD theses

- Design and engineering of a silicon strip detector for the high luminosity LHC
- Construction, commissioning and performance of the ATLAS Inner Tracker silicon strip detector

Table 3. Projected titles of ATLAS theses.

Figure 19. The Nikhef ATLAS group in 2011.

4.6 LHCb: Physics of Flavour

The LHCb collaboration was established in 1994 with Nikhef as a founding member; presently Nikhef is one of the 5 largest groups within LHCb. The LHCb collaboration consists of about 620 physicists, representing 63 different universities and laboratories (including 5 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[ref 8]. The Dutch LHCb group consists of physicists at the VU University Amsterdam, at the University of Groningen and at the Nikhef-FOM institute in Amsterdam. The groups of the VU and Nikhef are fully integrated, the RuG has recently joined the LHCb experiment associated to the Nikhef group. The groups in Amsterdam and Groningen plan to cooperate closely, in particular on the LHCb trigger and on lepton flavour physics.

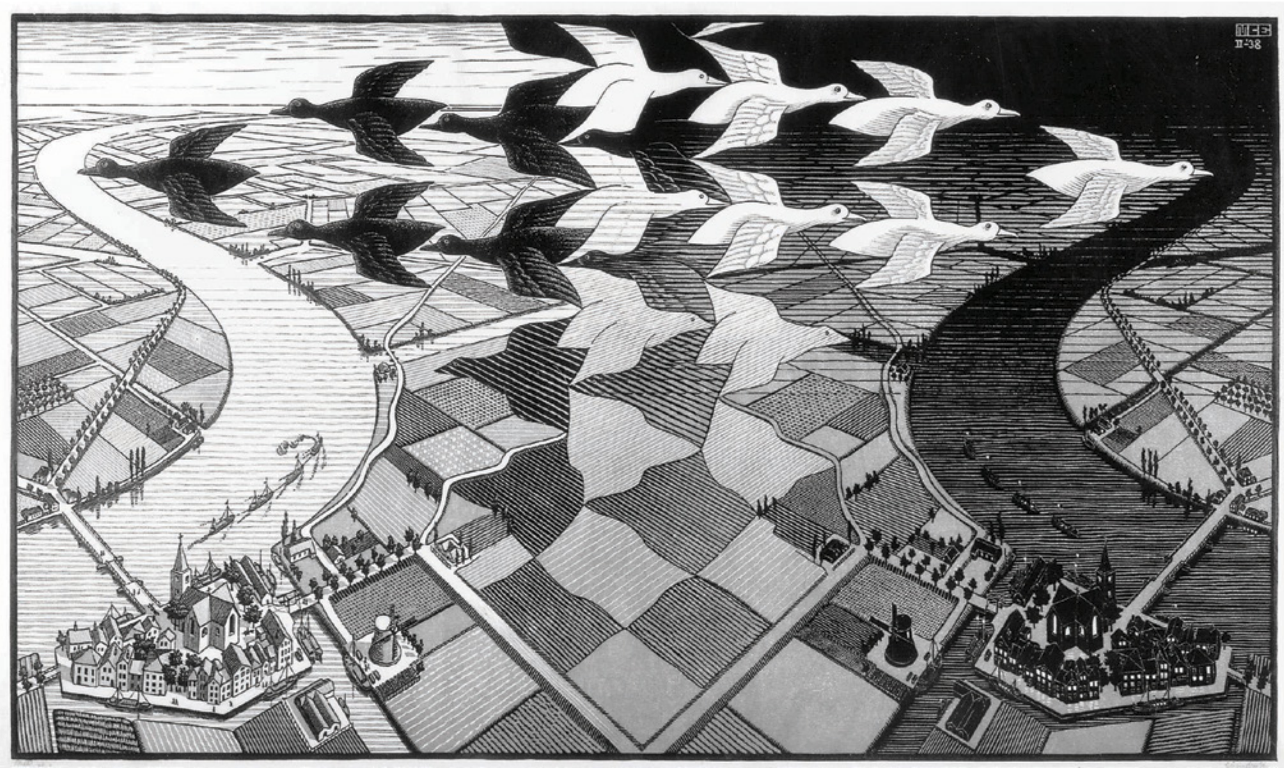


Figure 20. "Day and night", wood engraving by M.C. Escher, the black-white and left-right symmetry can be seen as an illustration of the almost perfect CP symmetry in nature.

In an early hot stage of the Big Bang the Universe was in a state where all particles were massless and the electromagnetic and weak forces were part of a single, unified electroweak force. When the Universe cooled down below a temperature equivalent to about 100 GeV, it underwent a phase transition during which the Higgs field acquired a non-zero vacuum expectation value. As a result of this phase transition, the carriers of the weak interaction, the $W^{\pm}$ and Z-bosons acquired mass, while the carrier of the electromagnetic interaction, the photon, remained massless. The original symmetry between the electromagnetic and weak interactions was spontaneously broken through interactions with the Higgs field.

In the Standard Model, the coupling of the same Higgs field to leptons and quarks provides an explanation not only how these matter particles acquire mass, but also causes matter and antimatter particles to interact differently with the weak force carriers. The latter breaks the symmetry between matter and antimatter particles, and is referred to as Charge-Parity (CP)-violation. An artistic representation is given above in Figure 20.

The part of the Standard Model that describes the interaction between quarks and the charged weak force carriers is called the Cabibbo-Kobayashi-Maskawa (CKM) mechanism, and, for it to allow CP violation, at least three generations of fundamental particles must exist. It was a striking success of the Standard Model when experiments at the LEP collider demonstrated that nature contains exactly three generations of light neutrinos, a result that was recently confirmed by observations of the cosmic microwave background by the Planck satellite.

Although the Standard Model allows for CP violation, what we know from the quark interactions falls short of explaining the observed scale of cosmic matter–antimatter asymmetry by many orders of magnitude. One of the fundamental puzzles in physics is whether the electroweak phase transition is solely responsible for the cosmic asymmetry, or whether it is caused by particles or forces beyond the Standard Model. The LHCb experiment is dedicated to understanding the physics of flavour changing interactions between quarks.

A. Scientific objectives and focus

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 charm quark, the third generation, and the high mass scale of the top. The discovery potential of flavour observables is an indispensable tool in the searches for New Physics at the LHC, and LHCb is the ideal instrument to realize that potential.

The primary goal of the LHCb experiment[ref 8] 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 these new heavy particles, LHCb searches for their virtual quantum effects via precision measurements in flavour-changing decays. The LHCb flavour physics programme in the quark sector focuses on two main themes:

- Searching for CP Violation phenomena that cannot be explained within the CKM-mechanism;
- Searching for rare, or even forbidden, decays that are incompatible with Standard Model predictions.

In both cases the presence of new particles in quantum loops can lead to unexpected observations. For CP violation this is signalled by particle-antiparticle asymmetries that deviate from their prediction, whereas in rare decays new couplings modify either the rate or the angular distribution of the decays, or both. Decays of beauty particles, and to a lesser extent charm particles, are particularly well suited to search for deviations of the Standard Model: they have a sufficiently large mass to allow precise predictions utilizing so-called heavy-quark effective theory. Using the LHC as the World's most prolific source of heavy-flavour particles, the LHCb collaboration pursues a wide range of CP-violation measurements in B-meson decays, charmed meson decays[ref 9] as well as in searches for rare decays.

B. Science challenges

Nikhef has made major investments in the LHCb experiment (Figure 21), contributing with a relatively large group, second only to the CERN group. The Dutch group includes a fully integrated team of physicists from Nikhef and the Vrije Universiteit Amsterdam, while recently two staff members of the University of Groningen joined the collaboration. The focus of the Dutch group is on the detection, reconstruction and physics of charged particles. The group including a fully integrated team of physicists at Nikhef and the VU, The leading contributions to the construction, installation and operation of the silicon Vertex Locator, the straw tubes Outer Tracker and the High Level Trigger are also reflected in several long-term leadership positions by Nikhef members. The Nikhef group has made major contributions to track reconstruction and online event reconstruction. In the physics analysis, our group focuses on physics channels that profit from the precise charged particle tracking measurements.

The physics programme of the Nikhef group is presently focused on B_s meson decays into charged particle final states. LHCb has access to an unprecedented sample of B_s mesons, which allows a precise study of the b-to-s quark transition. In various New Physics models this 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 CP-violation measurements of the CKM angle γ and the weak mixing phase φ_s, as well as the properties of the very rare decay $B_s \to \mu^+\mu^-$.

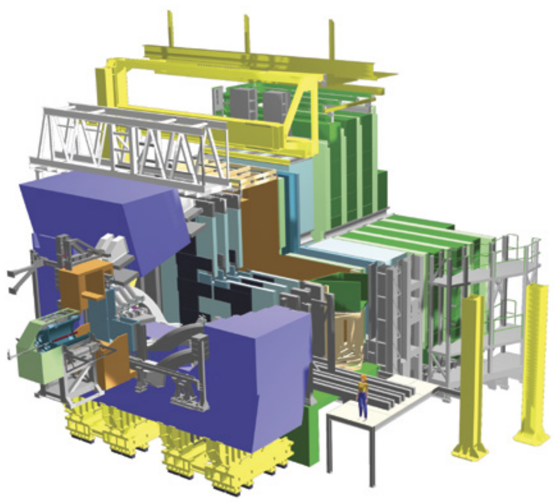


Figure 21. A schematic view of the LHCb detector.

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 tau decays.

Project 1. CP violation in the quark sector

The Standard Model, through the Cabibbo-Kobayashi-Maskawa (CKM) mechanism, predicts that relatively large CP-violating processes can occur in decays of B mesons. The size of asymmetries between particle and anti-particle decays is related to the complex phases of the CKM matrix elements, usually expressed in terms of the angles α, β and γ of the so-called unitarity triangle. Whereas the angle β has been measured by the B-factory experiments, the angle γ is still largely unknown. The current situation is illustrated in Figure 22.

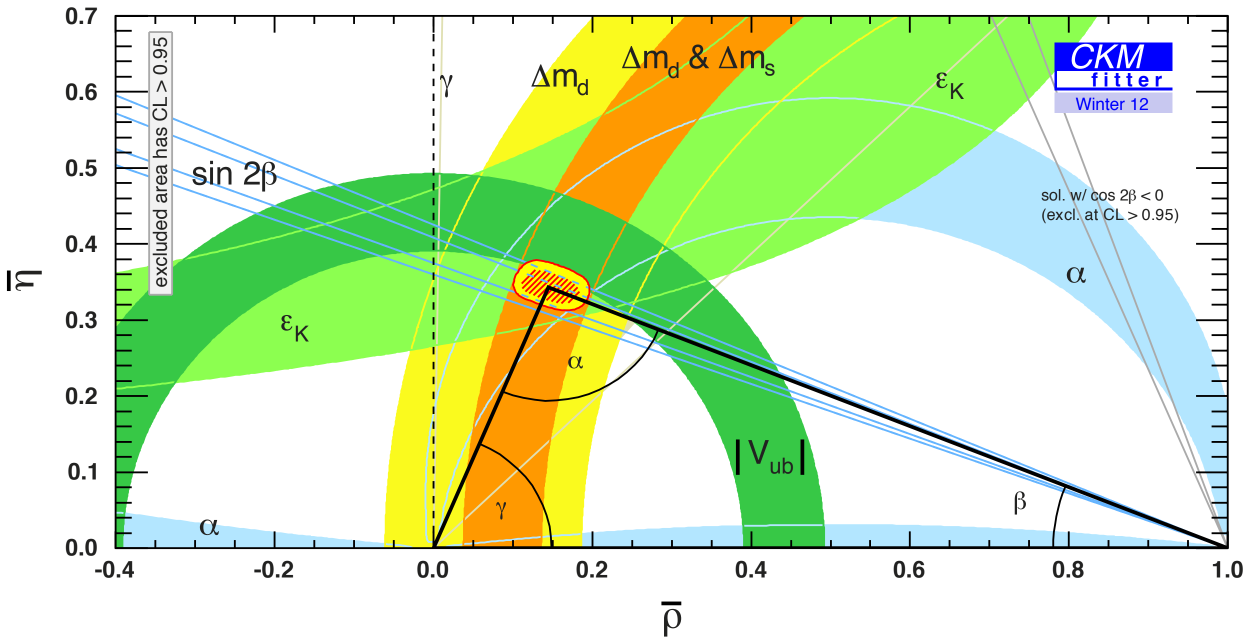


Figure 22. The unitarity triangle. Experimental constraints on the apex of the triangle are shown.

Similar to kaons, B^0 and B_s mesons can transform into their antiparticle (and vice versa) before they decay, a phenomenon called flavour oscillation. These oscillations allow CP violation to occur, via interference of different decay amplitudes, in case the mesons decay into a final state that is common to both B_s and anti-B_s particles. In the case of the B_s, CP violation is modulated coherently with the frequency of the B_s to anti-B_s oscillation process. These oscillations have been measured by LHCb and are found to have a frequency of 3×10^{12} Hz. The observed oscillation signal is shown in Figure 23.

We propose to perform a stringent test of the CKM prescription of CP violation by measuring the decay time-dependent CP asymmetry occurring in allowed B_s decays (so-called tree-decays) as well as that in suppressed B_s decays (so-called loop-decays). As loop decays are naturally sensitive to New Physics while tree decays are, by construction, dominated by Standard Model processes, the CKM model can thus be subjected to a stringent test, by comparing these measurements.

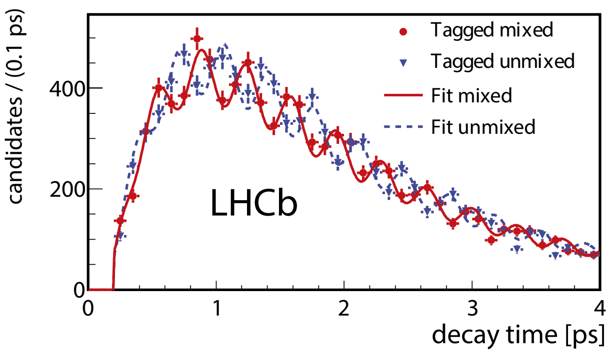


Figure 23. The decay-time dependent B_s to anti-B_s oscillations measurement. The red data and model are due to decays of B_s mesons that oscillated, while the blue data and model are due to decays that did not oscillate.

The physicists involved in project 1 are: P. Koppenburg (FOM), M. Merk (FOM & VU), G. Raven (VU), N. Tuning (FOM). For project 1 we request four PhD students and two postdocs. The specific expertise of the Nikhef group is in the analysis of B-decay time distribution, mass reconstruction, acceptance determination, event-likelihood fitting and penguin contributions. The proposed PhD projects are listed in Table 4.

1a. CP violation in tree-decays: completing the Standard Model picture

The first CP-violation project focuses on B_s-meson decays that are expected to be insensitive to contributions from New Physics. So called 'tree-diagram' processes contain no loops and are therefore not susceptible to quantum corrections of new particles. The measurements on these decays serve to perform a reference measurement of CP violation as induced by the known CKM description. This project will be carried out with a team of two staff members, two PhD students and a postdoc.

The method chosen by our group is a study of the decay-time dependent CP asymmetry observed in decays of a B_s meson into a strange-charm meson, the D_s, and a kaon: $B_s \to D_s K$. Due to the B_s–anti-B_s mixing oscillations, the expected CP-violating asymmetry is a function of the decay time of the observed decays. A clean observation of this decay-time dependent signal provides a theoretically and systematically accurate measurement of the angle γ of the CKM mechanism. A precise measurement of γ from these decays is crucial to complete the Standard Model description of CP violation in the quark sector and set the reference for measurements involving loop decays. Decays of the type $B_s \to D_s K$ have already been observed and their branching ratio has been measured by the members of our group, as shown in Figure 24. The Nikhef group is involved in the selection of the decays using boosted decision trees, as well as in the time-dependent analysis of the observed signal. A first CP-violation measurement is expected in the upcoming years, once the amount of collected data will be sufficiently large.

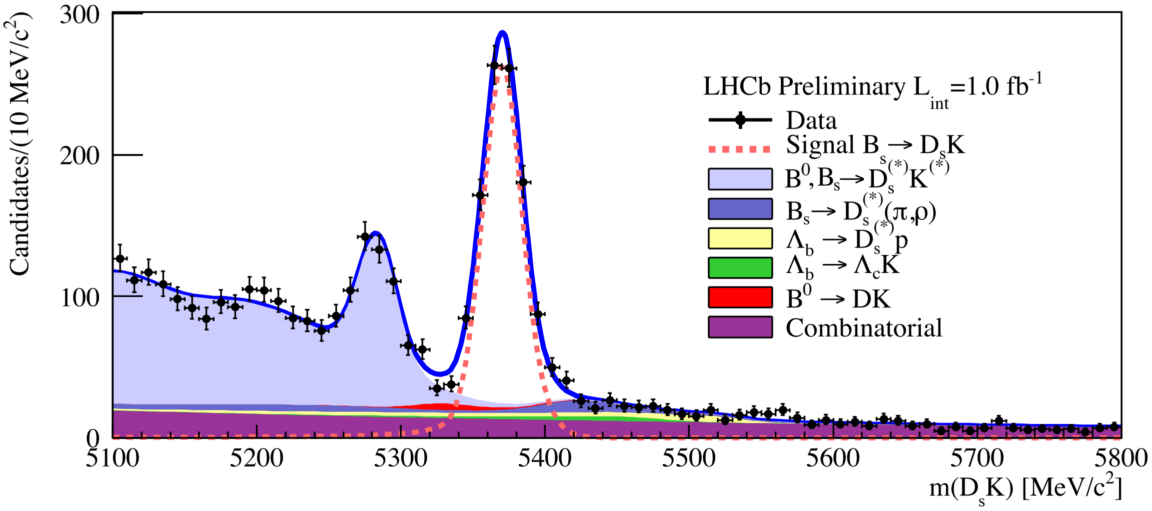


Figure 24. The observed peak of decays of the type $B_s \to D_s K$. The signal is shown by the red dotted line, various backgrounds are indicated by the coloured surfaces.

1b. CP violation in loop-decays: searching for New Physics

The second CP violation project studies decays that are specifically susceptible to contributions of New Physics. It focuses on the decays of B_s mesons into a final state that is a CP-eigenstate of two spin-1 ('vector') particles. Currently the focus is on CP violation in decays of B_s particles into a J/ψ particle and a φ ($B_s \to J/\psi\,\varphi$), while in the future the rare, so-called penguin-loop decays $B_s \to \varphi\varphi$ and $B_s \to K^*K^*$, see Figure 25, will be analysed. In both cases the decay process is sensitive to quantum loops that allow contributions from new, heavy particles. If such particles exist, they can give rise to a CP asymmetry that deviates from the expectation. This second CP-violation project will also be carried out by a team of two staff members, a postdoc and two PhD students.

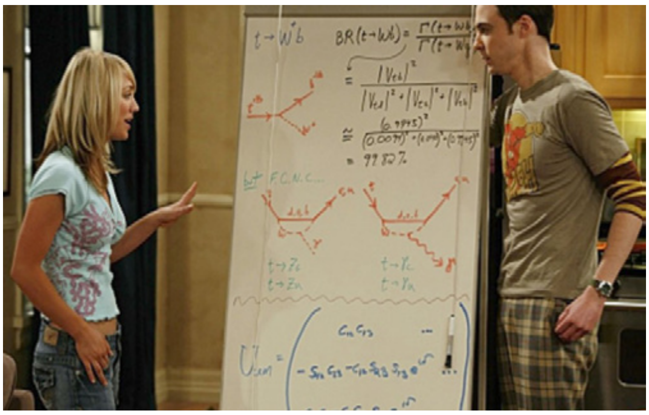


Figure 25. Penguin diagrams in "The Big Bang Theory".

Nikhef has developed a fitting program to extract CP-violation parameters from B decays into 'vector-vector' final state particles. In such decays the CP violation physics parameters are extracted by a combined analysis of the decay time distribution and the angular distribution of the produced particles. A study of $B_s \to J/\psi\ \varphi$ events has resulted in a CP-violation measurement that is with the present experimental accuracy, consistent with the Standard Model picture[ref 10]. The search for CP violation in the pure penguin mode, $B_s \to \varphi\varphi$, has recently led to the first publications, indicating that a high sensitivity will be possible in this mode.

Project 2. Rare decays

The Standard Model picture of flavour is based on a global flavour symmetry, broken by Yukawa interactions. In the quark sector this leads to a plethora of particle decays occurring via flavour-changing interactions that are mediated by the charge current (W-exchange) but suppressed in the neutral current (Z-exchange). In the lepton sector, the observation of neutrino oscillations implies that neutrinos have a tiny, but non-zero mass, which in turn implies that flavour-changing interactions for charged leptons exist in the Standard Model, albeit with minute branching ratios. We plan to study the quark sector primarily via the very rare decay $B \to \mu^+\mu^-$; for leptons we search for lepton-flavour and lepton-number violating decays.

The physicists involved in project 2 are: A. Pellegrino (FOM & RuG), W. Hulsbergen (FOM), G. Onderwater (RuG), H. Wilschut (RuG). We request for project 2 five PhD students and two postdocs. The PhD projects are listed in Table 4. The expertise of the group is in the study of fragmentation fractions, boosted decision trees and background composition.

2a. The very rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

The CKM mechanism and the absence of Flavour-Changing Neutral Currents (FCNC) at tree level, as described by the so-called GIM mechanism, are very distinctive features of the Standard Model. Does New Physics conform to this picture of flavour, thus confining possible sources of flavour breaking to the Standard Model Yukawa matrices? This fundamental question affects our understanding of the Universe and questions such as whether dark matter couples only to the Standard Model gauge bosons or to the Higgs, or may also couple directly to Standard Model matter, without leading to new sources of flavour violation. The LHCb experiment presents us with a unique opportunity to look for answers to these questions. The unprecedented size of the LHCb data sample makes it the perfect tool for the study of very rare decays of K, D, and B-mesons that may contain the key to the study of new sources of FCNC.

The most prominent example is the long-sought decay of neutral B mesons to a muon and an anti-muon pair. These are golden decays, since their branching fraction can be predicted extremely precise in the Standard Model: the purely leptonic final state confines theoretical uncertainties to measured parameters and the B-meson decay constant (obtainable from increasingly accurate lattice QCD calculations). The Standard Model prediction of a tiny branching fraction (at the level of once in a billion, due to angular momentum conservation and to the fact that it occurs only via loop diagrams) is to be contrasted with the large deviations predicted in New Physics models leading to new sources of FCNC (supersymmetry, two-Higgs doublets, Z' models, four-generations models, etc.). It is therefore no surprise that these decays receive wide theoretical attention.

Since the LHC start-up, the LHCb experiment has been the leader in the experimental search for the $B_s \to \mu^+\mu^-$ (Figure 26) and the $B^0 \to \mu^+\mu^-$ decays, setting more and more stringent limits on the size of their branching fractions, and recently the first evidence of the $B_s \to \mu^+\mu^-$ decay[ref 11] has been reported, albeit still with a large statistical uncertainty, see Figure 27. The Nikhef group (partly funded through the NWO "Vidi" program) has been at the forefront of this analysis, active in various aspects, including the measurement of the B-meson hadronization fractions, the branching fraction normalization, the detailed study of exclusive backgrounds and the statistical techniques for the extraction of confidence intervals.

The experimental results from the search for the $B_s \to \mu^+\mu^-$ and the $B^0 \to \mu^+\mu^-$ decays have received much attention in the media and been greeted as a death blow to New Physics models, most notably supersymmetry. However, this view is too simplistic: while it is true that some possible realizations of New Physics are strongly disfavoured by the data, the hunt has in fact only just begun! A complete realization of the potential of these decays requires not only the determination of their branching fractions, but also of their decay-time distribution and their CP asymmetry. Our strategy is two-fold: use all data we expect to collect with the present detector (about 10 fb^{-1}) to obtain the branching fractions of the $B_s \to \mu^+\mu^-$ and the $B^0 \to \mu^+\mu^-$ decays and their ratio; then aim at a ten-fold increase of the data sample with the upgraded LHCb detector, to gain access to the decay time and the CP-asymmetry observables[ref 12]. A group, consisting of two staff members, one postdoc and two PhD students, will ensure that we

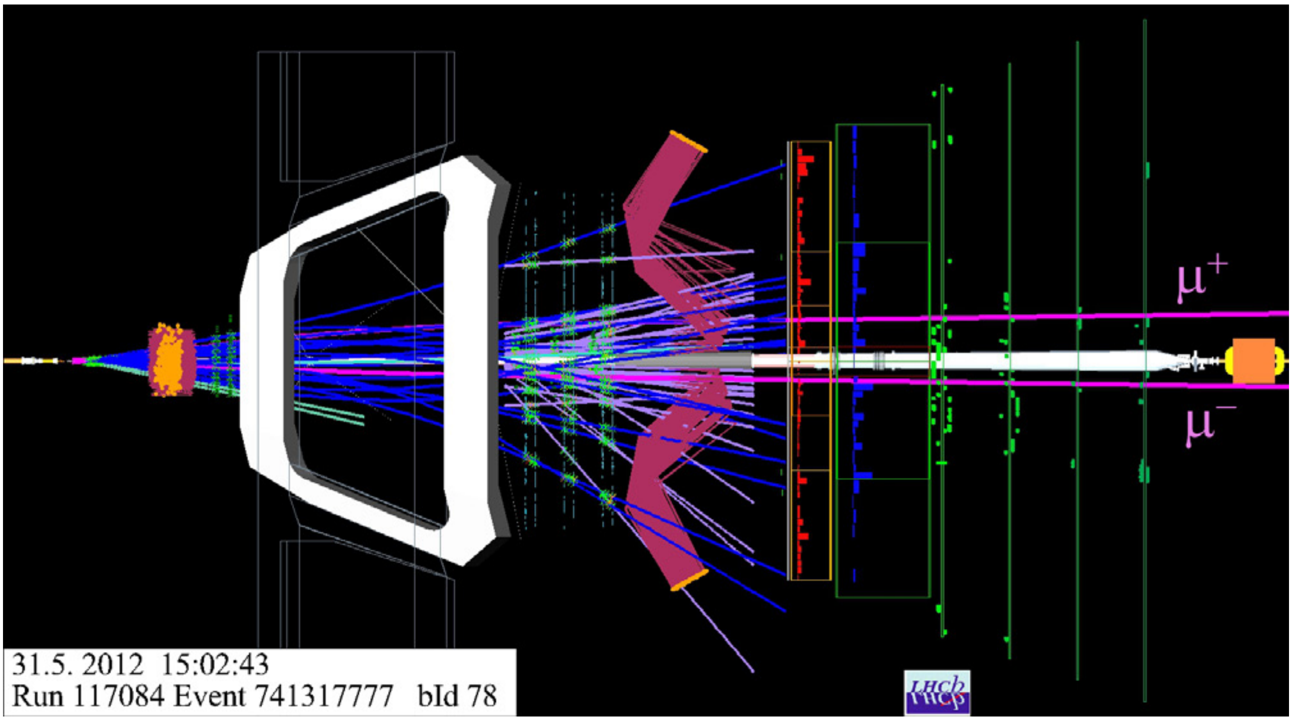


Figure 26. Graphic representation of a $B_s \to \mu^+\mu^-$ event candidate. This figure shows the detector hits and the reconstructed particle trajectories as blue curves. The two muon tracks are shown in purple.

maintain a leading position in these analyses, improving the treatment of the exclusive backgrounds, unifying the statistical approach to the determination of confidence intervals for both decays and their ratios, and strengthening our activity in phenomenological studies to maximize the impact of all experimental data (including B_s mixing and other $b \to s l^+ l^-$ decays like $B \to K^* \mu^+\mu^-$) on the search for physics beyond the Standard Model.

2b. Flavour physics in the lepton sector

An exciting frontier to explore in the hunt for New Physics is that of flavour-violating phenomena in the lepton sector. The occurrence of flavour-violating neutrino mixing implies a lepton-mixing mechanism similar to the one present in the quark sector. We propose to search for lepton-flavour-violating tau decays as well as lepton-number violating decays, which would establish the presence of Majorana neutrinos. The team includes three staff members, a postdoc and three PhD students.

LHCb is particularly suited for the measurements proposed due to its highly adaptive software trigger, which allows the selection of the signals in the presence of large backgrounds.

Lepton-flavour-violating decays are forbidden in the Standard Model, but can occur in New Physics models. Our extensive experience with the analysis of $B \to \mu^+\mu^-$ decays puts us in an excellent position to extend the search to flavour-violating $B \to e^+\mu^-$ decays. Moreover, we plan to exploit the prolific presence of tau leptons, which are produced by B and D meson decays. The sensitivity of LHCb in the search for $\tau^{\mp} \to \mu^{\mp}\mu^-\mu^+$ will surpass that of the B-factories in the upgrade phase of the experiment, due to the large integrated luminosity that is expected to be collected. The LHCb upgrade is estimated to be sensitive down to branching ratios of 10^{-9}.

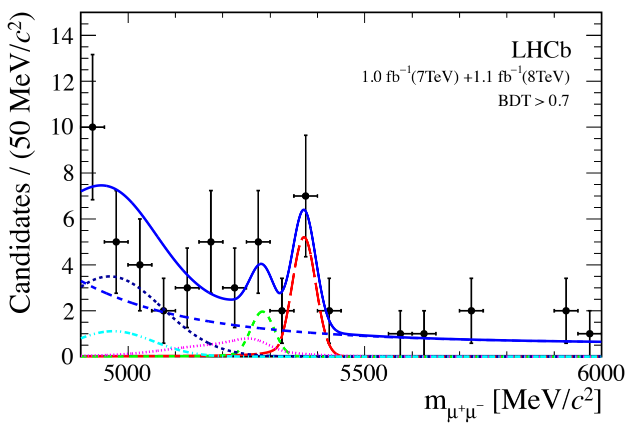


Figure 27. The observed $B_s \to \mu^+\mu^-$ signal as seen in the signal region of an optimised boosted decision tree method.

Heavy Majorana neutrinos occur in many New Physics models. It is quite possible that these particles have masses in the 1 GeV/c² range. A model that has received a lot of attention is the "Neutrino Minimal Standard Model" (νMSM) in which three Majorana-singlet fermions are added to the Standard Model. In this particular model, the lightest of the three has a mass in the keV/c^2 range and is a dark matter candidate, while the other two, heavier sterile neutrinos, can give mass to the Standard Model neutrinos via the see-saw mechanism at the electroweak scale. The requirement that baryogenesis occurs necessitates that the masses of the heavier two neutrinos be almost degenerate and O(1) GeV/c^2.

Heavy sterile neutrinos can be searched for in resonant contributions to lepton number violating processes such as $B^{\pm}\rightarrow\pi^{\mp}l^{\pm}l^{\pm}$ or $D_s^{\pm}\rightarrow\pi^{\mp}l^{\pm}l^{\pm}$. If this decay is mediated by a Majorana particle it can mix into a heavier neutrino, which can again decay into a hadron and a lepton. The distinctive signal of this decay is the resonant production of two like-sign leptons and an opposite-sign meson. The signature resembles that of neutrino-less double beta decay.

Nikhef group members are prominently active in the search for heavy Majorana neutrinos, in the context of a Vidi project searching for heavy, exotic particles. We plan to pursue this activity and include the search for lepton flavour violation, in particular for the upgraded experiment.

C. Technology challenges

The LHCb spectrometer is designed to detect decays of beauty and charm mesons. The experiment has fulfilled the promises of excellent vertex detection and momentum measurement of charged particles. It includes subsystems that cleanly perform particle-identification of electrons, muons, photons, pions and kaons. To successfully select the decays of interest from the backgrounds the experiment has a sophisticated online trigger.

The LHCb collaboration foresees an upgraded experiment including a major redesign of the readout electronics and a trigger based on the concept of a trigger-less Front-End readout at the LHC bunch crossing frequency of 40 MHz, followed by a purely software trigger. Whereas the current experiment exploits a rich flavour physics programme in the quark sector, this upgrade allows to further extend the sensitivity for New Physics searches with quarks, and to implement a lepton-flavour based physics programme[ref 14].

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) but also to online 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 8 mm from the LHC beams. During injection of the LHC beams the detectors are retracted to a safe position at 3 cm. The open/close system, which positions

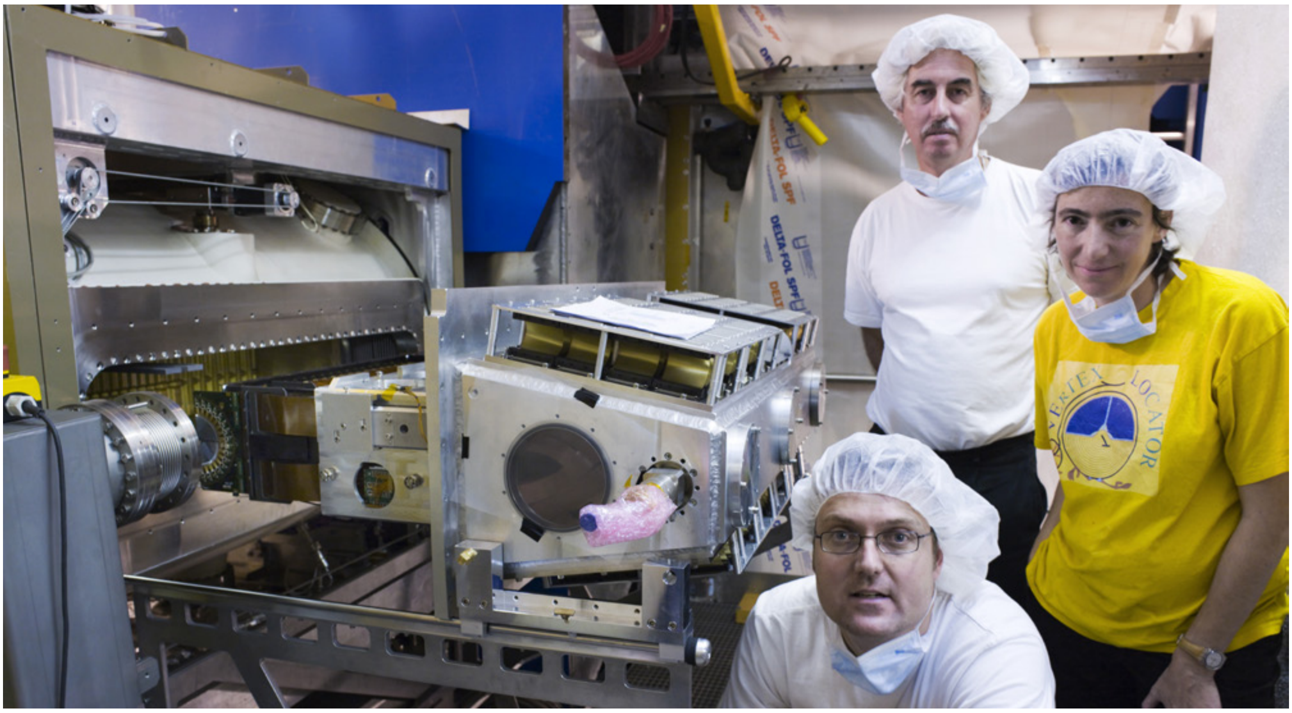


Figure 28. Nikhef technicians install the first half of the LHCb Vertex Locator (VELO) detector.

the detector with an accuracy of 5 μm, was also designed and built at Nikhef. Due to their 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 a binary-phase CO_2 cooling technique developed by Nikhef. This technology is currently being adopted by the other LHC experiments.

The momentum of charged particles is determined by measuring their deflection whilst traversing a large magnetic dipole field. Nikhef was the leading institute designing and constructing the Outer Tracker, a system of twelve planes of straw tubes (55,000 tubes in total, covering about 30 m^2) that allow to measure the tracks with about 70 μm resolution leading to a track momentum resolution of $\delta p/p = 0.5\%$.

To complement our detector hardware investments in tracking detectors Nikhef invested in the offline (initially) and online (more recently) reconstruction of charged particle trajectories. In particular a state-of-the-art Kalman filter algorithm has been developed allowing trajectory fitting including scattering kinks and simultaneous alignment of subdetector systems.

Figure 29 illustrates the tracking performance of LHCb by means of its invariant mass resolution: the individual peaks of the Upsilon 1S, 2S and 3S resonances are clearly resolved.

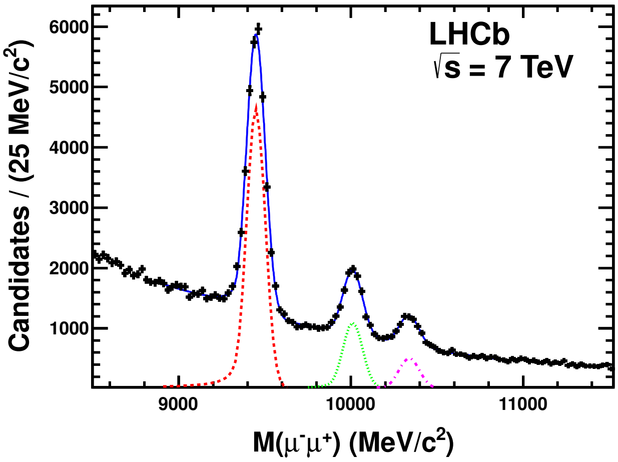


Figure 29. Reconstruction of the di-muon invariant mass illustrating the resolution to observe the Upsilon 1S, 2S and 3S resonances.

Project 3. The LHCb detector upgrade

While all crucial ingredients of the LHCb detector (vertex and momentum resolution, particle identification, triggering) work at their best, the collaboration has drawn an upgrade plan to realize a 10-fold increase of data samples after collecting O(10 fb^{-1}) with the current detector. Exploiting the flexibility of the before-mentioned readout and trigger upgrade, LHCb will become a general purpose detector for the forward rapidity region.

The upgraded experiment includes new tracking detectors, a possible replacement of RICH-1 detector, new front-end electronics and a new trigger system. The Nikhef group intends to take a leading role in the new tracking detectors and in the trigger. A new VELO detector, based on pixel technology and positioned even closer to the beam-line, will lead to an improved vertex reconstruction performance. The straw-based momentum tracker will be replaced by a higher granularity scintillating-fibre tracker, capable of operating in a higher particle-density environment. Finally, our group sees an opportunity to improve the trigger capabilities by implementing a massive multi-core GPU version of the high level trigger.

Preparations for the upgrade have already started[ref 14] and the Nikhef group aims to use part of the requested manpower for the upgrade. Various members of our staff are active in upgrade projects (VELO, OT, trigger) and we foresee contributions of the requested PhD students and postdocs. For the students this implies typically that they will include one or two chapters on detector research in their PhD dissertation. Three dedicated PhD students are requested, one for each project: VELO, OT, trigger.

The following physicists participate in this project 3: M. v. Beuzekom (FOM), E. Jans (FOM), Part-time: W. Hulsbergen (FOM), M. Merk (FOM & VU), G. Onderwater (RuG), A. Pellegrino (FOM & RuG), G. Raven (VU), N. Tuning (FOM). For the project we request three PhD students. The PhD projects are listed in Table 4. The Nikhef expertise is in the following technical sectors: electronics, CO_2 cooling, vacuum technology, silicon detectors, straw tube detectors and trigger algorithms.

D. Theses projects

CP violation PhD theses

- Measurement of time dependent CP violation using the tree-dominated decay: $B_s \to D_s K$
- Exploring CP Violation using $B^0 \to D^+D^-$ and $B_s \to D_s^+ D_s^-$ decays
- A high precision measurement of CP violation in B_s mixing
- CP violation in Penguin loop dominated decays using $B_s \to \varphi\varphi$ and $B_s \to K^*K^*$ events

Rare decays & exotica PhD theses

- Determination of the $B_s \to \mu\mu$ and $B^0 \to \mu\mu$ branching fractions and their ratio as a probe of New Physics
- Measurement of the effective lifetime of $B_s \to \mu\mu$ events: a search for non-standard decay couplings
- A search for lepton flavour violation in $B \to e^+\mu^-$ and $\tau \to 3\mu$ decays
- A model independent search for long lived heavy particles at the LHC
- Search for Majorana neutrinos in lepton number violating B and D decays

Detector upgrade PhD theses

- A novel fibre tracker detector for charge particle tracking in LHCb
- Construction and commissioning of a silicon pixel vertex detector for online vertex reconstruction in LHCb
- Development of a GPU multicore technology based High Level Trigger for the LHCb experiment

Table 4. Projected titles of LHCb theses.

Figure 30. The Nikhef LHCb group in 2012.

4.7 ALICE: Quark Gluon Plasma, a new State of Matter

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 10 largest groups within ALICE. The main aim of the collaboration is to study 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 m meters wide and 26 m meters long, and weighs approximately 10,000 tons[ref 15].

A. Scientific objectives and focus

In the world around us, quarks and gluons do not exist as free particles because they are permanently bound into hadrons by the strong interaction. At very high temperatures and densities however, hadronic matter is expected to undergo a phase transition to a new state of matter –the Quark-Gluon Plasma (QGP)– where quark and gluon degrees of freedom are not anymore confined inside the hadrons. Such temperatures and densities were present in the early Universe until the first microseconds after the Big Bang. Not only in the early Universe, but also in heavy-ion collisions at ultra-relativistic energies it is possible to reach temperatures and densities well above the phase-transition point. The highest temperatures and energy densities are currently reached in collisions of heavy-ions at the LHC. At the LHC, the ALICE detector is built to precisely measure the properties of the QGP and the QCD phase transition. This includes measurements of the phase transition temperature and energy density, of the relevant degrees of freedom (hadronic or partonic), and of the transport properties of the QGP such as the speed of sound.

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 on the interactions of the QGP with so-called hard probes.

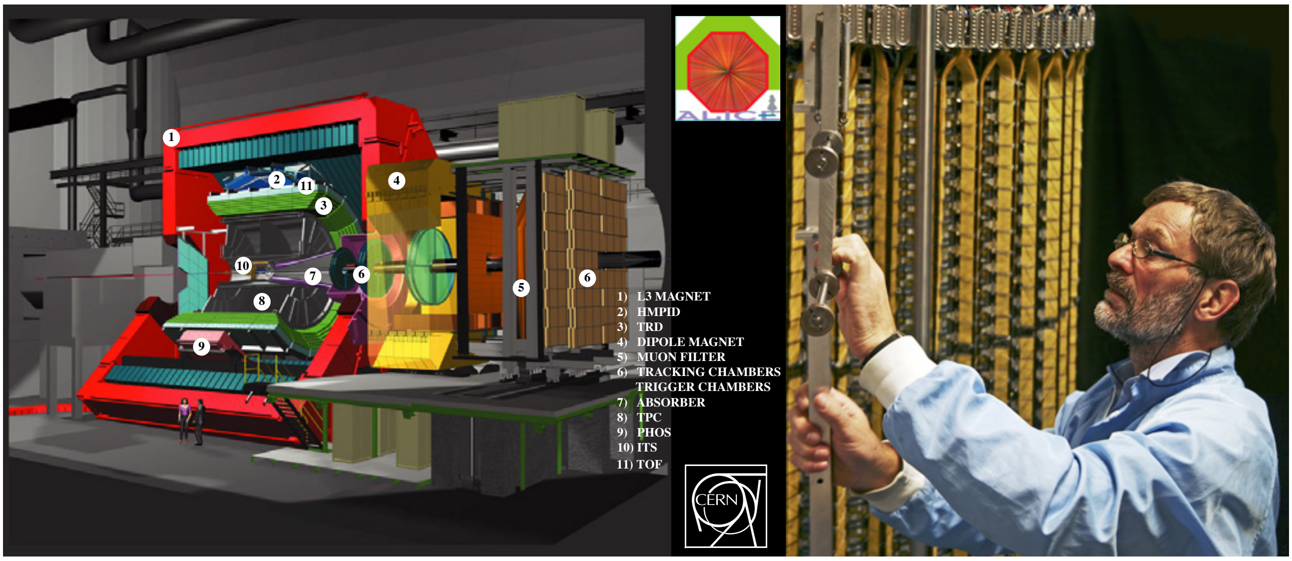


Figure 31. Left: The ALICE detector layout. Right: A Nikhef technician assembling the silicon strip detectors.

As in the early Universe, the hot and dense system created in a heavy-ion collision will expand and cool down. This collective expansion (so-called flow[ref 16,17]) is driven by the pressure gradients so that the measurement of flow can provide experimental information on the equation of state and on the transport properties of the created QGP. The most pronounced experimental signature of flow in heavy-ion collisions is the azimuthal anisotropy in particle production. This, because for most collisions the overlap region of the colliding heavy-ions is not spherically symmetric. This leads to asymmetric pressure gradients in the collision region, and to an azimuthal asymmetry in the momenta of the produced particles. An harmonic analysis of the angular correlations gives experimental access to the details of the collective anisotropic expansion, which can then be interpreted in terms of relativistic hydrodynamics. The harmonic analysis makes use of sophisticated multi-particle correlation techniques that were partially developed by the group at Nikhef[ref 18]. At present, the flow analysis at the LHC has confirmed an earlier finding at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven, USA. Contrary to expectations, the QGP seems to behave as an almost-perfect inviscid liquid. 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 Nikhef group also uses multi-particle correlations to search for parity violating effects in the strong interaction. As far as we know, CP is conserved in the strong interaction but it is argued that in the vicinity of the de-confinement phase transition the QCD vacuum could create regimes, local in space and time, which exhibit CP violating effects. These effects would lead to differences in azimuthal correlations between same- and opposite-charged particles along the direction of the strong magnetic field created in non-central heavy-ion collisions. This phenomenon is called the chiral magnetic effect (CME) and the search for this effect by the Nikhef group is currently in progress.

The QGP can also be studied via its interaction with 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 (charm and bottom) 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 interactions (jet quenching). The goal of jet quenching measurements is first to verify our theoretical understanding of the energy loss mechanism, and then to 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 make reliable jet measurements possible. Heavy quarks, like charm and bottom, are clean and penetrating probes to study the properties of the QGP. This is so because heavy quarks are predominantly produced at the early stage of the collision –when there is enough energy available– so that they probe the QGP during almost its entire lifetime. 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, for precision measurements of hadrons containing charm and bottom quarks.

B. Science challenges

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 is used to relate the measurements to the properties of the medium created in the collisions. This makes heavy-ion physics a very challenging but rich multidisciplinary field based on perturbative QCD, lattice QCD, particle physics, nuclear physics, the AdS/CFT correspondence, thermodynamics and relativistic hydrodynamics.

Another, experimentally challenging, aspect is that one has to deal with a very crowded environment where thousands of charged particles are produced in one heavy-ion collision. The trajectories of all these particles must be reconstructed with sufficient precision to distinguish those produced in the interaction region from those decaying in flight. A strong feature of the ALICE detector is that it can reconstruct particles down to very low momenta –where the bulk of the particle production takes place– and that it has excellent capabilities to identify the particle species of the reconstructed tracks.

In terms of hardware, the Nikhef group has contributed to the ALICE inner tracking system (ITS) by playing a leading role in the design and construction of the two outer layers of silicon strip detector (SSD). The ITS is the most lightweight tracker of its kind and is extremely important for charged particle tracking and is 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 which functions extremely well. Our focus point on heavy quark production in heavy-ion collisions nicely matches our past hardware effort in the ITS, and improvements in the analysis of heavy quark production is a strong motivation for our involvement in the future ITS upgrade.

From the many observables that probe the properties of the QGP, the measurement of anisotropic flow probably has had the highest impact in the last decade. It led to the finding at RHIC that the medium created in ultra-relativistic heavy-ion collisions behaves –unexpectedly– as an almost perfect liquid. This finding 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, in the STAR experiment at RHIC, played a major role in the analysis of anisotropic flow, and continue to do so in ALICE. Prior to the first data taking at the LHC, the Nikhef group developed the flow analysis software for ALICE leading to a publication[ref 19], a few days after the first Pb+Pb collisions, that confirmed the findings at RHIC. This publication is currently the highest cited ALICE physics paper, and is still one of the highest cited papers at the LHC.

Flow is a genuine multi-particle correlation but a straightforward N-particle correlation analysis would need N! operations on a computer, which is impossible in the case of a heavy-ion collision where there are a few thousand tracks in an event. 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 specialised subject and the Nikhef group is in close contact with experts in the field to further develop the techniques and to implement these in the ALICE software.

Because flow is closely related to the geometry of the collision, a by-product of the flow analysis methods is the access to important orientation axes in a collision, like the orientation of the reaction plane spanned by the beam axis and the impact parameter that connects the centre of the colliding nuclei. Exploration of the sensitivity of observables to the reaction plane opens the road to very interesting physics analyses like the investigation of the chiral magnetic effect, and the study of the reaction plane correlation in heavy-quark production, to see if heavy quarks participate in the flow. Jet production in elementary collisions is calculable in perturbative QCD so that these calculations –together with measurements in proton-proton and proton-nucleus collisions– form a baseline for the understanding of jet suppression in heavy-ion collisions. Jets are difficult to identify in the crowded environment of a heavy-ion collision and only at the LHC they sufficiently stand out to perform a detailed analysis of jet production. Heavy-ion jet analysis is, in fact, quite a novel field where ALICE, with its low momentum tracking, can contribute by measuring soft gluon radiation from jets, and thereby gain insight in the quenching mechanisms. We are actively involved in the ALICE jet analysis group with one of our group members acting as a convenor.

Our involvement in the analysis of heavy-quark production naturally correlates with the ITS hardware efforts, but also dates back to the strong involvement of Nikhef group members in the analysis of STAR data at RHIC. Heavy quarks uniquely probe the QGP and it is of interest to not only measure heavy-quark production with respect to elementary proton-proton interactions, but also to measure this with respect to the main axes of an heavy-ion event.

We propose two projects in the field of heavy-ion physics for which we request eight PhD and two postdoc positions.

Project 1. The study of angular correlations

The following physicists will be part of the project: M. Botje (FOM), P. Christakoglou (FOM), P. Kuijer (FOM), R.J.M. Snellings (UU). For this project we request four PhD students and one postdoc. The proposed PhD projects are listed in Table 5.

The aim of this project is to characterise the main QGP transport coefficients by measuring the full spectrum of anisotropic flow fluctuations and their correlations using novel multi-particle techniques, and to search for novel effects in the strong interaction.

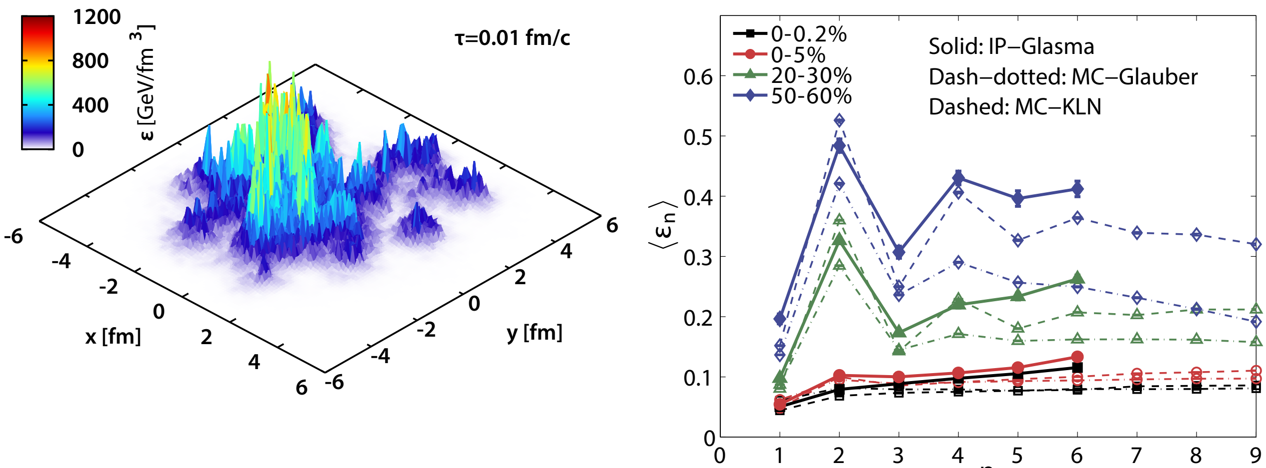


Figure 32. Left: Typical transverse energy density profile for a non-central collision. Right: Primordial fluctuation power spectrum of the matter created in Pb+Pb collisions at the LHC for different centralities, from three different initial state models.

1a. Anisotropic flow
The flow analysis makes use of sophisticated statistical techniques that measure azimuthal correlations between the produced particles. These techniques were developed in part by the Nikhef group[ref 18] and led to the first ALICE paper on elliptic flow at the LHC[ref 19]. This publication is currently the highest cited ALICE physics paper.

The left panel of Figure 32 shows the energy density distribution in the transverse overlap region of two colliding nuclei. This distribution can be described in terms of Fourier coefficients, which are shown in the right panel of Figure 32. For a smooth elliptic overlap region the odd Fourier coefficients would be zero, because of symmetry. In reality however, the collision region has a complicated structure that gives rise to large non-zero odd and higher order harmonics. This is shown in Figure 32 for three models of the colliding nuclei. A low shear viscosity over entropy ratio of the QGP causes these higher harmonics to survive in the final distribution of the produced particles. The Nikhef ALICE group has developed the tools to fully exploit the Fourier spectrum of anisotropic flow coefficients and thereby get a handle on the shear viscosity of the QGP, and the initial energy density distribution.

In ALICE, the anisotropic flow analysis is done in the correlations and fluctuations physics working group, which is led by the convenor R.J.M. Snellings from Nikhef.

1b. Chiral Magnetic Effect
Two- and multi-particle angular correlations are used by the Nikhef group to investigate possible signatures of parity violation in the strong interaction. ALICE measurements have shown a charge separation qualitatively consistent with expectations from the CME. While these results are tantalising, they so far did not provide solid evidence for CP violation in the strong interaction and ongoing analyses aim to differentiate between the contributions from conventional physics and the CME.

Project 2. Study of the QGP interaction with hard probes
The following physicists will be part of the project: M. Botje (FOM), P. Kuijer (FOM), M. van Leeuwen (FOM), A. Mischke (UU), T. Peitzmann (UU). For this project we request four PhD students and one postdoc. The proposed PhD projects are listed in Table 5.

The aim of this project is to study the parton energy loss mechanism from precision measurements of jet production in heavy-ion collisions, and to study the production of prompt D and B mesons to probe in-medium heavy quark thermalisation and the quark mass dependence of energy loss mechanisms.

2a. Jet quenching
The initial measurements of jet quenching have been performed in an indirect way without full jet reconstruction. To better understand the energy loss mechanism, full reconstruction of jets is crucial but this is a very challenging task in the crowded environment of a heavy-ion event. Energetic jets are easier to reconstruct and are more abundant at the LHC compared to RHIC. The Nikhef group is actively involved in measurements using reconstructed jets and new methods are being developed to remove the effect of the large background of uncorrelated particles that are also produced in the collision.

The left panel of Figure 33 shows the current measurements of normalised jet spectra reconstructed from charged particles in central and more peripheral Pb+Pb collisions. The ratio of the two spectra is plotted in the right panel of Figure 33 and shows a strong deviation from unity. This indicates that a sizable fraction of the original parton energy is redistributed to fragments that have low momentum or emerge at large angles outside the jet cone. To test the relation between jet quenching and the medium density, detailed measurements of the jet spectra should be extended to the future LHC energies of 5.5 TeV. This analysis will ultimately lead to a measurement of the density of thermal quarks and gluons inside the QGP.

Nikhef plays a dominant role in these studies and M. van Leeuwen is a convenor of the jet physics working group in ALICE.

2b. Heavy quarks
Heavy-quark energy loss can shed light on the energy-loss mechanism, as shown by QCD calculations of gluon Bremsstrahlung that predict a characteristic quark-mass dependence due to the so-called dead-cone effect. The Nikhef group focuses in ALICE on the measurement of charged D^* meson production. Recently published results show that the charm energy loss is large (see Figure 34), although there is a possible indication that charm pro-

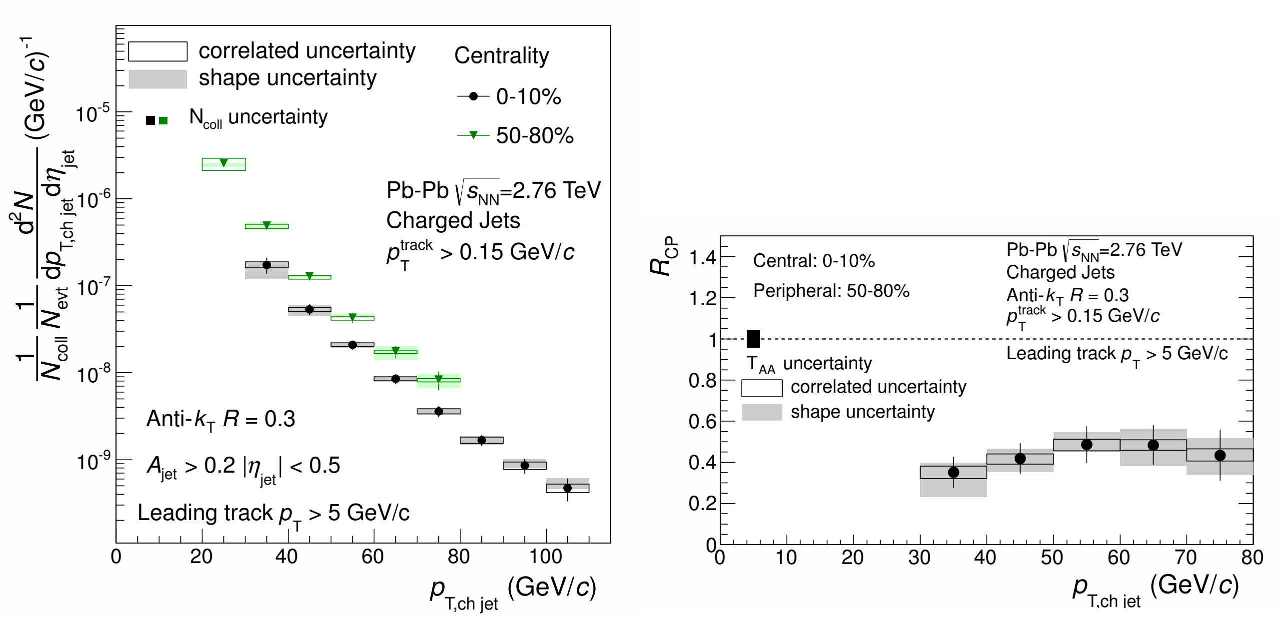


Figure 33. Left panel: transverse momentum distribution of jets reconstructed from charged particles measured by ALICE in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, for central (0-10%) and peripheral collisions (50-80%). The distributions are normalised per nucleon-nucleon collision. Right panel: ratio of the spectra in central and peripheral collisions: nuclear modification factor R_{CP} as a function of transverse momentum.

duction is less suppressed than light-quark hadrons at low transverse momentum. This is in line with expectation from the dead-cone effect, but more data are needed for final conclusions.

In addition the Nikhef group measured a non-zero azimuthal anisotropy of D^0 and D^* production, which shows that these particles participate in the collective expansion of the medium. This is of considerable interest because the magnitude of collective flow as function of the quark mass is a sensitive probe of the degree of thermalisation of the QGP. A more detailed study requires a large statistics comparison of the charm flow with respect to that of the light quarks.

The upcoming runs with Pb+Pb collisions at 5.5 TeV will improve our statistics. Precision measurements of heavy quarks do, however, require an upgrade of the ALICE inner tracking system. This future upgrade will also give access to the production of B mesons.

C. Technology challenges

As a dedicated heavy-ion experiment, the specifications of ALICE differ from those of the other LHC experiments. The ALICE detector was designed to cope with huge multiplicities of up to 20,000 charged tracks in one central Pb+Pb collision. In addition, heavy-ion physics requires excellent particle identification over a broad momentum range, covering both light particles at high momentum, and heavy particles (containing charm and beauty quarks) down to very low momentum. In the first years of running, the ALICE detector has demonstrated excellent performance, even exceeding most of its design goals.

The current ALICE detector is, however, limited in the maximum event rate it is able to handle. To make full use of the future high luminosity in heavy-ion collisions, the ALICE collaboration has proposed a strategy for upgrading the central ALICE detector [ref 20]. The increased luminosity of the heavy-ion runs after 2018 will lead to

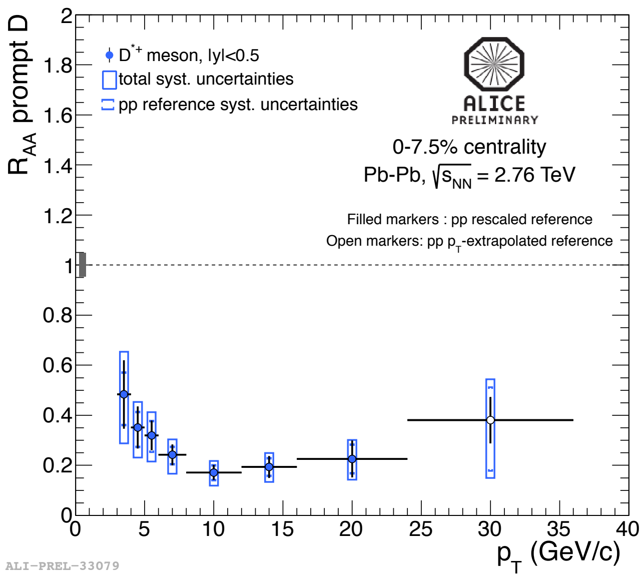


Figure 34. Nuclear modification factor R_{AA} of the D^{*+} meson as function of transverse momentum.

interaction rates of about 50 kHz, which is almost two orders of magnitude larger than what ALICE is currently able to handle. Because many of the observables involve complicated probes at low transverse momentum, traditional methods for triggering cannot be used. The upgraded ALICE detector must therefore be in a position to record every collision, which amounts to about 10^{10} interactions and an integrated luminosity of 10 nb^{-1}. This large sample of recorded events will allow us to perform the measurements discussed in the previous sections with sufficient statistical accuracy.

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

Project 3: Inner Tracker System (ITS) upgrade

The following physicists will be part of the project: P. Christakoglou (FOM), P. Kuijer (FOM), R.J.M. Snellings (UU). For this project we request two PhD students and one postdoc. The proposed PhD projects are listed in Table 5.

P. Kuijer is the convenor for the upgrade of the outer layers of the ITS and T. Peitzmann is the convenor of the ALICE detector upgrade working group.

Nikhef has significantly contributed to the existing ITS. Because we play a leading role in the ALICE physics analysis after the detector upgrade, it is our ambition to also significantly participate in the upgrade of the ITS. Because of our proven leadership and technical experience gained during the design and production of the existing outer layers of the ITS, we are able to play a leading role in the design and construction of the outer layers of the new ITS. Currently, the Nikhef ALICE group contributes to studies of the ITS physics performance for open beauty production and heavy-flavour jet identification. Figure 35 shows the expected large improvement in the low transverse momentum tracking efficiency with the new ITS.

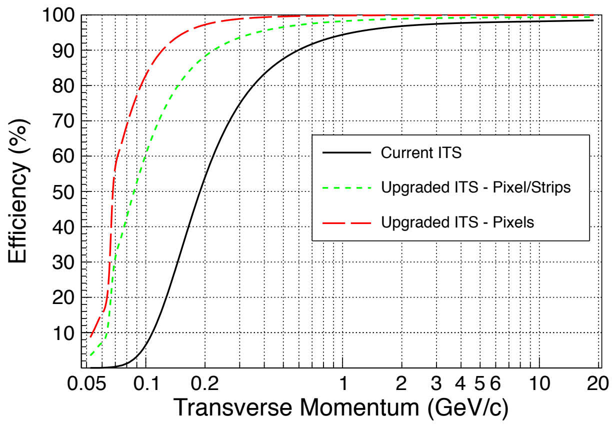


Figure 35. Simulation studies of the tracking efficiency at low transverse momentum with the ITS upgrade (using different types of silicon technologies), compared to the current ITS (black curve). From current studies an improvement of the D^{*+} reconstruction efficiency at low p_T by a factor of about 25 is expected.

Figure 36. The Nikhef ALICE group in 2013.

D. Theses projects

Angular correlations and the Chiral Magnetic Effect (CME) PhD theses

- Searching for CME signatures with charge-dependent correlations
- Anisotropic flow measurements of D mesons
- Anisotropic flow fluctuations measured using multi-particle correlations
- Angular correlations and fluctuations in particle production in pp, pA and Pb+Pb collisions

Jet quenching and heavy quarks PhD theses

- Heavy flavour energy loss: R_{AA} from beauty and charm
- Heavy flavour fragmentation in pp and Pb+Pb collisions
- Exploring the gluon radiation in jets in heavy-ion collisions
- Jet fragmentation with identified particles in heavy-ion collisions

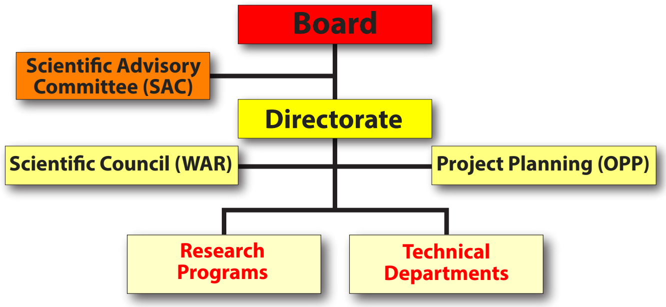
Inner Tracker System upgrade PhD theses

- Anisotropic flow measurements of B mesons
- Λ_C and D_s production in heavy-ion collisions

Table 5. Projected titles of ALICE theses.

5 Management of the Programme

A. The Nikhef collaboration



The LHC projects typically fall within the realm of 'Big Science'. Big Science projects require long-term planning, international collaboration, and significant investments. For this reason almost forty years ago the Dutch research groups active in this field joined forces and formed the Nikhef collaboration. Currently the Nikhef collaboration consists of FOM (through its FOM-institute Nikhef) and four universities: the VU University Amsterdam (VU); the University of Amsterdam (UvA); the Radboud University Nijmegen (RU); and the Utrecht University (UU), governed by the Nikhef Collaboration agreement. The Nikhef model is nationally and internationally regarded as exemplary for how a country can have a stronger impact in international big science projects. In the following the Nikhef governance is briefly described.

The *Board* of the Nikhef collaboration consists of representatives of FOM and the partner universities. The Board, meeting at least once a year, is responsible for the approval of the scientific programme and the corresponding (multi-annual) budget, as proposed by the *Directorate*. Nikhef's external *Scientific Advisory Committee* (SAC), composed of renowned international experts in the field, yearly provides a report to the Board, covering the complete scientific programme. New research initiatives are scrutinized on various levels. The internal *Scientific Council* (WAR) will be the first to advise the director regarding upcoming scientific opportunities. Once the director decides to pursue an option, he presents it to the SAC. If the SAC, taking into account scientific merit, manpower requirements and availability, and investment prospects, gives a positive recommendation, the director prepares a proposal to the Board as part of the scientific programme and budget, and gets approval (or not). All this can take place on short notice and allows Nikhef to make swift decisions if needed. Technical contributions are realized in project teams consisting of physicists, engineers and technicians and, if necessary, conflicts between projects are discussed and resolved in the regular *Project Planning* (OPP) meetings in which all project leaders, the heads of technical departments and the Directorate participate.

Each main research activity or programme is coordinated by a *Program leader* appointed by the director. The program leaders have, within budgetary constraints, significant autonomy. Each year every program leader discusses the details of his/her programme with the directorate. In shaping the Nikhef collaboration there have always been opportunities for each university partner to choose a particular research profile. Each university partner therefore typically focuses on two experimental research activities (at present one in accelerator-based particle physics and one in astroparticle physics) and most of the programmes are in fact led by a university professor. Currently there are expressions of interest from Leiden University (UL) and University of Groningen (RuG) to join the Nikhef collaboration.

B. The LHC physics programme

The proposed programme will fit seamlessly in the existing Nikhef governance structure. The overall leader of the LHC physics programme will be the Nikhef director. The Nikhef director has the authority to amend the programme and rebalance between the experiments, all within the governance and advisory boundaries as sketched previously.

The day-to-day leadership of each of the three experiments will be delegated to a program leader (see Table 6), which will have the same autonomy as other program leaders within Nikhef. For the largest Nikhef involvement (ATLAS) two program leaders have been appointed, with and between whom a clear separation of duties has been agreed.

	ATLAS	LHCb	ALICE
Program leaders	Prof.dr. Paul de Jong (UvA) Prof.dr. Nicolo de Groot (RU)	Prof.dr. Marcel Merk (FOM & VU)	Prof.dr. Raimond Snellings (UU)
Nikhef Partners	FOM-institute, UvA, RU	FOM-institute, VU, (RuG)	FOM-institute, UU

Table 6. Program leaders per LHC experiment.

The LHC collaborations are all structured along the same lines. The governing body is the Collaboration Board (CB) in which all participating institutes are represented. Nikhef thus has one seat in the CB. Day to day management of the collaboration is in the hands of an (elected) spokesperson and his or her management team. Dedicated groups are installed for specific subdetector design, construction and/or analysis activities. Financial matters, such as the level of Maintenance and Operations (M&O) costs are decided upon in the 'Resources Review Board' (RRB), one for each collaboration and represented per country, with meetings twice a year. The Nikhef director represents The Netherlands in these RRBs.

Although formally the influence of the Nikhef in the LHC collaborations is not larger than any other institute ('one man one vote'), Nikhef staff have influential positions within the collaborations. Table 7 gives an overview of key positions of Nikhef staff in the three LHC collaborations. Nikhef's track record in the LHC experiments provides clear evidence of this influence.

	Detector-related positions	**Physics-related positions**
ATLAS	Detector upgrade coordinator: N. Hessey Computing coordinator: K. Bos Member of speakers bureau: P. Ferrari Member of publications committee: P. de Jong Member of collaboration board advisory committee: S. Bentvelsen, P. de Jong	Top quark physics group coordinator: S. Bentvelsen, P. Ferrari, W. Verkerke SUSY physics group coordinator: P. de Jong Astroparticle forum coordinator: D. Berge Combined muon performance group coordinator: P. Kluit, W. Liebig Flavor-tagging group coordinator: F. Filthaut Trigger menu coordinator: O. Igonkina Top reconstruction group coordinator: I. van Vulpen Susy missing-E_t subgroup coordinator: S. Caron
LHCb	Outer Tracker project leader: A. Pellegrino, N. Tuning Velo 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 (Track) Reconstruction coordinator: M. Merk, W. Hulsbergen, M. Martinelli Editorial board: N. Tuning Physics analysis convenors: • Time Dependent CP violation and Mixing: G. Raven, W. Hulsbergen • QCD, Electroweak and Exotica: V. Coco • B decays to charmonia: D.M. Santos
ALICE	Deputy spokes person: P. Kuijer Upgrade coordinator: Th. Peitzmann Project Leader Silicon Strip Detector: P. Kuijer, G.-J. Nooren First run coordinator: P. Kuijer	Physics Working Group convenor: M. van Leeuwen, R. Snellings Physics Board: M. van Leeuwen, T. Peitzmann, R. Snellings Physics Analysis Group convener: P. Christakoglou Editorial board chair: P. Kuijer Conference Committee: P. Christakoglou

Table 7. Overview of (present and former) key positions of Nikhef staff in the three LHC collaborations.

In summary

The proposed research programme is led by the director of Nikhef, Prof.dr. F. Linde, who carries the full executive responsibility. The responsibility for the local tasks of the physics programme of each experiment is on the shoulders of the present program leaders. Administrative support is given by the coordinating institution, the FOM Institute for Subatomic Physics Nikhef, in Amsterdam. Points of joint management interest are:

- The available resources will be allocated as described in Section 6 of this proposal, but subject to a reevaluation on an annual basis;
- Each PhD student will be associated with the research school 'OSAF'. The research school provides graduate courses and will monitor the progress of each student;
- Scientific progress will be exchanged on a quarterly basis in open meetings of all participants;
- The Nikhef Scientific Advisory Committee (SAC) will monitor and review progress on an annual basis;
- Scientific publications resulting from research are subject to the internal review system of the three collaborations;
- Co-program leaders inform the program leader over scientific output and budget allocations.

6 Budget

A. Overview

The planned effort in the LHC experiments for the period 2014–2021 can be fairly well derived from Nikhef's experience in the years 2000–2012. In these years design, construction and analysis efforts have taken place. Averaged these years the directly attributable effort has been 8.2 M€ per year across the whole of the Nikhef collaboration. 'Directly' here means: excluding overhead and excluding activities from (grid) computing, R&D and Theory, which –of course– have also contributed greatly to the success of the LHC experiments (and will continue to do so in the future). This amount is also excluding hardware investments in the LHC detectors, which have totalled around 18 M€ in the 2000-2010 period.

From this 8.2 M€ annually about 3.2 M€ came as FOM-programme funding, meaning that the remainder has been provided through the institute's mission budget, university *('1e geldstroom')* contributions and project funding, such as NWO *'Vernieuwingsimpulsen'*, FOM *'Projectruimten'* and European projects. The project funding stream has increased in size and importance – to illustrate: for the year 2012 about 1.5 M€ of the direct LHC efforts has been funded through such project funding.

Given the budgetary constraints (in particular the indications given by FOM for the future LHC physics programme budget) and to allow for the balance with the astroparticle physics ambitions of Nikhef, we expect for 2014–2021 –compared to the previous period– a down-sized fundable effort for the LHC experiments (upgrades and continued analysis of the data).

Therefore, the Nikhef collaboration will continue to seek additional funding for its LHC ambitions. A *'Zwaartekracht'*-proposal, covering a 10 year period and aiming for 30 M€ subsidy with an emphasis on scientific staff (tenure track positions, postdocs and PhD positions) in the astroparticle physics sector of Nikhef, has recently been submitted to NWO. This proposal covers and extends Nikhef's scientific programme and as such –if granted– will likely alleviate some of the budgetary constraints in the proposed LHC program.

Nikhef staff members will also continue to pursue funding from national (NWO *'Vernieuwingsimpuls'*) and European (ERC) personal grants and from every other funding possibility that may arise.

For the upgrades of the LHC detector a proposal will be submitted later this year to NWO's 'Large Research Infrastructures' call. The LHC experiments are eligible for funding, because they have been included on the National Roadmap, following our proposal two years ago. Nikhef aims for a budget request in the order of 16 M€, to cover both the cost of investment in the LHC detectors and continued investment in the computing facilities (Tier-1), aligned with the national e-Infrastructure, to which Nikhef has contributed greatly in the last decade.

B. Summary budget request (FOM part only)

Table 8 shows the budget request for each of the three LHC experiments (ATLAS, LHCb and ALICE respectively). The personnel budget is exclusively reserved for PhD students (54 k€/year) and postdocs (70 k€/year). Other scientific staff, technical and engineering staff etc. will be funded through the mission budget and university contributions.

A ratio of about 3:1 (PhD students:postdocs) has been demonstrated to be desirable, especially since coaching PhD students during their CERN stay is predominantly done by postdocs stationed at CERN. Following the usual practice of having PhD students stationed at CERN for on average a year and postdocs for two to three years, we have also provided for an additional personnel budget to cover these secondment costs (estimated at 15 k€ per secondment year).

The distribution of PhD students and postdocs over the three experiments basically is a continuation of the sound experience in the last decade and is perfectly aligned with the aspired Nikhef-position in each of the experiments. Within certain boundaries Nikhef staff have freedom to choose the experiment, for which they are personally most motivated and feel they can make a difference. Also the university partners have certain preferences (see also paragraph 5 for the distribution of management responsibilities): the groups from the UvA and RU, having been active in DELPHI and L3 in the LEP era, are now heavily involved in ATLAS, whilst the VU and UU, coming from a nuclear physics background, have shifted to LHCb and ALICE respectively. In terms of effort this leads to a ratio ATLAS:LHCb:ALICE of about 5:3:2, which is also reflected in the temporary scientific staff distribution.

The requested material budgets are dominated by two item lines: Nikhef's share in the Maintenance and Operations (M&O) costs of the experiments and travel budget. These have always been part of the FOM-programme budget and we propose to continue this for the new LHC physics program.

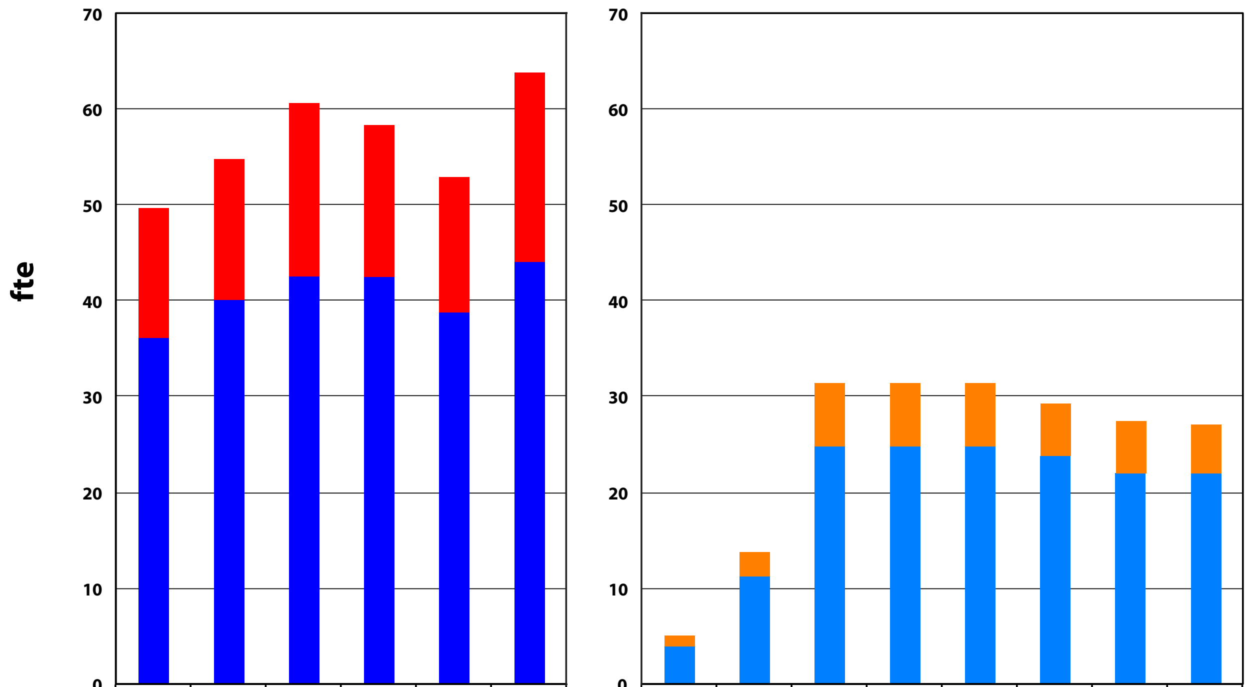
The M&O-costs scale with the number of staff having a PhD or equivalent degree on the author list of each experiment (PhD students participate for free). The estimates are based on Nikhef's current permanent staff involvement in the experiments (which we expect to continue at about the same level), the budgeted number of postdocs and on the current (2013) total M&O costs of the three experiments (which is also expected to be stable in the coming decade).

The travel budgets cover the travel cost of the permanent scientific staff, postdoc and PhD positions as requested in the LHC physics program. Based on current experience an average of 4 k€ travel budget per year per fte is assumed.

It should be noted, that other material costs, that will be incurred (such as R&D budget for the detector upgrades, travel costs for technical and engineering staff) will be borne by the mission budget (including moderate investments).

For historical reasons the current FOM-programme funding for ALICE ends in 2013, for LHCb in 2014 and for ATLAS in 2015. Therefore the funding request for ALICE starts in 2014, for LHCb in 2015 and for ATLAS in 2016. The new programme runs until 2021; the presently foreseen start of the long (two-year) shutdown to prepare the LHC machine and notably the ATLAS experiment for high-luminosity LHC operations to allow a further tenfold increase of the overall data sample.

The total budget request amounts to 16.9 M€ of which roughly 45% is devoted to ATLAS, 30% to LHCb and 25% to ALICE. After the initial years (in which step wise the three experiments are funded), the desired ratio of 5:3:2 (ATLAS:LHCb:ALICE) will be reached.



	2007	2008	2009	2010	2011	2012
postdocs	13.5	14.7	18.1	15.9	14.2	19.6
PhD students	36.1	40.1	42.5	42.5	38.7	44.1

	2014	2015	2016	2017	2018	2019	2020	2021
postdocs	1	2.5	6.5	6.5	6.5	5.5	5.5	5.0
PhD students	4	11	25	25	25	24	23	23

Figure 37. Past (left) and projected (right) numbers (this proposal only) of postdocs (red, orange) and PhD students (blue).

The left hand part of Figure 37 shows the total number of postdocs and PhD students over the period of 2007–2012 funded through both the current FOM programmes and all additional acquired projects. The right hand part shows the number of postdocs and PhD students requested in the new LHC physics programme proposal in the years 2014–2021. The graph shows, that in order to just maintain the current temporary scientific staff size in the LHC experiments, a sizable fraction (about a third to a half) of all effort needs to be acquired from additional (non-FOM programme) funding schemes.

ATLAS	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**total**
senior staff (memorandum item)			17.0	17.0	17.0	17.0	17.0	17.0	
PhD students			12.0	12.0	12.0	12.0	12.0	12.0	**18.0**
postdocs			3.0	3.0	3.0	3.0	3.0	3.0	**6.0**
secondment years			5.0	5.0	5.0	5.0	5.0	5.0	
personnel budget (including secondment)			933	933	933	933	933	933	**5,598**
running budget – M&O			191	191	191	191	191	191	**1,143**
running budget – travel			128	128	128	128	128	128	**768**
LHCb	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**total**
senior staff (memorandum item)		11.0	11.0	11.0	11.0	11.0	11.0	11.0	
PhD students		6.0	7.0	7.0	7.0	7.0	7.0	7.0	**12.0**
postdocs		1.5	2.0	2.0	2.0	1.5	1.5	1.5	**4.0**
secondment years		2.5	3.1	3.1	3.1	2.8	2.8	2.8	
personnel budget (including secondment)		467	564	564	564	524	524	524	**3,732**
running budget – M&O		126	131	131	131	126	126	126	**894**
running budget – travel		74	80	80	80	78	78	78	**548**
ALICE	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**total**
senior staff (memorandum item)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	
PhD students	4.0	5.0	6.0	6.0	6.0	5.0	4.0	4.0	**10.0**
postdocs	1.0	1.0	1.5	1.5	1.5	1.0	1.0	0.5	**3.0**
secondment years	1.7	1.9	2.5	2.5	2.5	1.9	1.7	1.3	
personnel budget (including secondment)	311	369	467	467	467	369	311	271	**3,030**
running budget – M&O	86	86	91	91	91	86	86	81	**697**
running budget – travel	52	56	62	62	62	56	52	50	**452**

Per cost category	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**total**
personnel budget (including secondment)	311	835	1,964	1,964	1,964	1,826	1,768	1,728	**12,360**
running budget – M&O	86	212	412	412	412	402	402	397	**2,735**
running budget – travel	52	130	270	270	270	262	258	256	**1,768**

Per experiment	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**total**
ATLAS			1,252	1,252	1,252	1,252	1,252	1,252	**7,509**
LHCb		666	775	775	775	728	728	728	**5,174**
ALICE	449	511	619	619	619	511	449	402	**4,179**
Total	***449***	***1,177***	***2,646***	***2,646***	***2,646***	***2,490***	***2,428***	***2,382***	***16,863***

Table 8. Budget request for the LHC programme (fte & k€).

C. Alternative budget scenario with imposed budget ceiling

The FOM-board is concerned that, given Nikhef's long-term funding perspective, Nikhef's astroparticle physics activities could be compromised once the full 16.86 M€, as requested in this proposal for LHC physics, is granted. With the foreseen Nikhef budget ceiling on FOM-programs, the available funding for future astroparticle activities might become insufficient. The FOM-board has therefore requested Nikhef to put forward an alternative budget scenario with a maximum integral expenditure of 15 M€. On paper this is a simple exercise with a cut of about 6–8 of the requested 53 temporary scientific (PhD and postdoc) positions. As such, this has been implemented in Table 9 by reducing the budgets of the LHC groups in proportion. Detailed fine-tuning is not appropriate at this moment. Since astroparticle physics activities at Nikhef are not at immediate risk, scientific positions (four of the 40 PhD positions and three of the 13 postdoc positions) have been cut primarily in the second half of the envisaged programme period, *i.e.* from 2017 till 2021 resulting in an overall budget of 14.98 M€.

Only recently (Fall of 2009), the LHC entered, after almost 20 years of preparations and huge investments, its exploitation phase, *i.e.* the time when notably PhD students are crucial, performing very rewarding tasks such as participating in the Higgs analysis! This is also visible in Nikhef's publication record illustrated in Figure 42 on page 51; since the LHC turn-on the number of publications in refereed journals has increased enormously (and is far larger than the corresponding number of publications by Nikhef's astroparticle physics activities). This is also why accelerator-based particle physics, and in particular CERN's LHC experiments, has been and will remain to be for the foreseeable future Nikhef's highest priority research topic and even the main reason of Nikhef's existence: to coordinate the Dutch activities at CERN. It should be clear that the research ambitions described in Sections 4.5-4.7 of this programme proposal, already assume that, in addition to the scientific positions funded by this FOM-programme application, Nikhef will be able to attract significant additional funding from various other open competition sources (*FOM-Projectruimte*, *NWO-Vernieuwingsimpuls*, *EU-Framework* programs), as stipulated in the budget paragraph, Section 6. In the recent past, these additional sources typically comprised about 30% of the LHC-related temporary scientific positions at Nikhef. Attracting these funds has been a real challenge. In the future it will be even more challenging, since already the requested 16.86 M€ overall budget represents an almost 20% reduction compared to Nikhef's present baseline LHC budget, *i.e.* the soon expiring ATLAS, LHCb and ALICE FOM programme budgets. A further reduction of the FOM-programme budget, as addressed in this section, will reduce Nikhef's perspective to attract additional funding correspondingly. This because notably postdocs have generally excellent opportunities in the various open competition funding schemes. Astroparticle physics activities, despite their tantalizing and important discovery potential, should not jeopardize Nikhef's CERN-based activities by a too severe reduction of Nikhef's baseline LHC exploitation budget. This LHC physics FOM-programme should not be underbudgeted at a time when the LHC has only just started operations.

Nikhef is actively looking into alternative (*i.e.* non-FOM) ways of funding its activities and notably its astroparticle activities. One large funding proposal has already been submitted within the NWO-Gravitation scheme and will be decided upon by December 2013[1]. If this and other future funding opportunities all fail, Nikhef's astroparticle physics activities come at risk. An ideal time to review our strategy and in particular the balance between Nikhef's accelerator-based (*i.e.* LHC) and astroparticle activities will be around 2017–2018 when:

- the first results of LHC-running at or near design energy are expected to be available;
- the Virgo gravitational-wave search is expected to make its first observation;
- the XENON direct dark-matter search will have completed its first science run;
- the future of Nikhef's deep-sea neutrino-telescope programme (KM3NeT) and Nikhef's long-term perspective in radio detection of cosmic-rays (Auger) will be much clearer than at this moment.

In conclusion, Nikhef strongly feels that a decision about a reduced Dutch presence at CERN in general and at the LHC in particular should be postponed. The 2017–2018 period appears the right moment for an evaluation and possibly a revised funding decision regarding Nikhef's LHC activities. Around the same time also the status of the International Linear Collider (ILC) project and notably Japan's position herein will be clear. Incidentally, this period also coincides with Nikhef's next important evaluation by NWO which takes place every 6–7 years; the last one was in 2011.

1 The NWO-Gravitation proposal titled *"NL-APP: Crossing the frontiers of astroparticle & particle physics"* was submitted by a nationwide consortium of particle physicists, astroparticle physicists and astronomers. The proposal, if granted, will significantly boost and thereby secure notably (but not exclusively) astroparticle physics research in the Netherlands by opening 10 tenure track, 32 postdoc and 44 PhD positions in the coming decade (of which typically 70% would land at the present Nikhef consortium members).

Atlas	2014	2015	2016	2017	2018	2019	2020	2021	total
senior staff (memorandum item)			17.0	17.0	17.0	17.0	17.0	17.0	
PhD students			11.0	11.0	11.0	11.0	10.0	10.0	**16.0**
postdocs			3.0	3.0	3.0	2.0	2.0	2.0	**5.0**
secondment years			4.8	4.8	4.8	4.1	3.8	3.8	
personnel budget (including secondment)			875	875	875	795	738	738	**4,896**
running budget – M&O			191	191	191	181	181	181	**1,115**
running budget – travel			124	124	124	120	116	116	**724**
LHCb	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	
senior staff (memorandum item)		11.0	11.0	11.0	10.0	10.0	10.0	10.0	
PhD students		6.0	7.0	7.0	6.0	6.0	6.0	6.0	**11.0**
postdocs		1.5	2.0	2.0	1.5	1.0	1.0		**3.0**
secondment years		2.5	3.1	3.1	2.5	2.2	2.2	1.5	
personnel budget (including secondment)		467	564	564	467	427	427	347	**3,261**
running budget – M&O		126	131	131	116	111	111	100	**824**
running budget – travel		74	80	80	70	68	68	64	**504**
Alice	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	
senior staff (memorandum item)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	
PhD students	4.0	5.0	6.0	5.0	5.0	4.0	4.0	3.0	**9.0**
postdocs	0.5	1.0	1.0	1.0	1.0	1.0	0.5		**2.0**
secondment years	1.3	1.9	2.2	1.9	1.9	1.7	1.3	0.8	
personnel budget (including secondment)	271	369	427	369	369	311	271	173	**2,559**
running budget – M&O	81	86	86	86	86	86	81	76	**668**
running budget – travel	50	56	60	56	56	52	50	44	**424**

Per cost category	2014	2015	2016	2017	2018	2019	2020	2021	total
personnel budget (including secondment)	271	835	1,866	1,808	1,711	1,533	1,435	1,257	**10,716**
running budget – M&O	81	212	407	407	392	377	373	358	**2,607**
running budget – travel	50	130	264	260	250	240	234	224	**1,652**

Per experiment	2014	2015	2016	2017	2018	2019	2020	2021	total
Atlas			1,190	1,190	1,190	1,096	1,035	1,035	**6,735**
LHCb		666	775	775	652	605	605	511	**4,589**
Alice	402	511	572	511	511	449	402	294	**3,651**
LHC Physics – Total	***402***	***1,177***	***2,537***	***2,475***	***2,353***	***2,150***	***2,042***	***1,839***	***14,975***

Table 9. Alternative budget scenario for the LHC programme (fte & k€).

7 Application Perspective

"…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, 'Babbage' blog about the LHC project, 20-5-2011.

The primary focus of this proposal is curiosity driven research, in short: "*What is the Universe made of?"* and "*How does it 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 and society at large. Thanks to CERN's Large Hadron Collider 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

Our researchers engage in many different manners with the general public. In addition to the standard public lectures and interviews in the usual media like newspapers, magazines, radio and television, our researchers now also perform in science cafés and pop temples like *Paradiso* and *Paard van Troje* throughout the Netherlands 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"* (featured on Dutch television the same evening CERN announced the Higgs discovery) as the undisputed highlight. Another novelty was *Cosmic Sensation* –a multi-day silent disco in a large dome-shaped tent with the music and light show steered by and visualizing the passage of cosmic-rays. This last event was awarded the prestigious "*Academische Jaarprijs"* for the best science inspired outreach activity in 2009. 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, covering in popular language elementary particle physics from the discovery of the electron in 1897 to the Higgs discovery in 2012 and beyond. 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.

Figure 38. Outreach activities to the public range from astrophysics for high schools to lectures for children.

Outreach to youth

Apart from the outreach activities aimed at the general public, we have special programs targeting children and high-school students (and sometimes their teachers). For kids we collaborate with the NEMO science museum in Amsterdam. We constructed a large spark chamber setup for the visualization of cosmic-rays and we donated a cloud chamber showing the presence of numerous ionizing particles in our everyday environment. Operated by people from NEMO, these detectors now form the main attraction in a hands-on cosmic-ray experience. NEMO also organizes the so-called monthly "*Wakker Worden Kinderlezing"* (Wake up Lecture) for 8–12 year young children in which our researchers regularly appear with topics like: *What is the origin of lightning?; Can you measure what you cannot see?; Why do you float on the Dead Sea?* When science inspired movies (*e.g. The Fantastic 4; Angels & Demons*) have their first viewings, we are also frequently asked to separate fact from fiction herein. The annual "*Techniektoernooi"*, a technical competition (paper bridges; balloon cars; air-pressure rockets; *etc.*) for elementary school pupils, was long-time chaired by one of us and to date many of us still take part in this annual national event wearing our formal university gowns. We also have and will again collaborate with the makers of

"*Klokhuis"*, a programme aimed primarily at elementary school kids to explain all kinds of interesting phenomena. One episode featured the Nikhef director colliding head-on with the "*Klokhuis"* host on in-line skates inside the LHC tunnel. New episodes are being planned together with Nikhef scientists.

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 that have a particle physics content like the measurement of the muon lifetime and guided tours to CERN. In addition, one of us chairs the organization responsible for the www.natuurkunde.nl and www.sciencespace.nl websites, aimed at high-school students with the goal to stimulate interest in science. Nikhef initiated and runs the HiSPARC (High School Project on Astrophysics Research with Cosmics) project, in which high-schools install large scintillator slabs in ski-boxes on their school's rooftop. These detectors are connected to an (inter)national network, giving the students of the schools the opportunity to study high-energy cosmic-rays. At present, about 100 stations are installed in the Netherlands. Every year, about seven high-school teachers spend a stage (one day per week) at Nikhef to further expand HiSPARC's possibilities. High-school teachers are also sponsored by Nikhef to take part in high-school teacher events at CERN. Nikhef staff members were also involved in shaping the new physics high-school curriculum that is to start in September 2013 and in producing modules for the high-school curriculum on Nature, Life and Technology (NLT). One of the co-applicants is the director of the Radboud Pre-University College of Science, streamlining all activities of the Radboud University's faculty of science with high schools.

Links through the national e-Infrastructure

The data volumes and computing requirements of the LHC experiments have been the driving force in the development of the Dutch e-Infrastructure for data processing. BiG Grid is a project founded by Nikhef, NBIC (Netherlands Bio-informatics Centre) and NCF (National Computing Facilities), with SURFsara as an operational partner, for building the data-intensive computing infrastructure. It was expressly constructed as a multidisciplinary facility from its inception in 2006 and includes the Dutch LHC Tier-1 grid computing facility in the Netherlands. Although the LHC experiments were (and still are) the largest consumers, it gives today thousands of researchers, from over 40 distinct communities including astroparticle physics, astronomy, the life sciences, the humanities, civil engineering, and econometric studies, access to grid, cloud and open-source software hadoop services. The BiG Grid facilities are now an integral part of the national e-Infrastructure, governed by SURF.

Having particle physics as an early adopter and primary driver of the e-Infrastructure has been crucial for its success in other domains. The methodology used in the preparation for the LHC data was one of 'data challenges' and 'service challenges' of continually increasing scope and size. This method has been re-used in preparing for the radio-astronomy data avalanche for the LOFAR archive. Data access and integrity processing developed at Nikhef for managing large volumes of data in long-term archives has been deployed for the DANS (*Data Archiving and Networked Services*) back-end storage, thus ensuring data stored there are verifiably correct. The security and authorization technologies developed to allow ten thousand physicists, spread across more than 150 particle-physics institutes and over 50 countries and economic regions, to cooperate in sharing data and computing capacity has been used as the basis for the authorization service in CLARIN, the ESFRI project on common language resources and technology infrastructure.

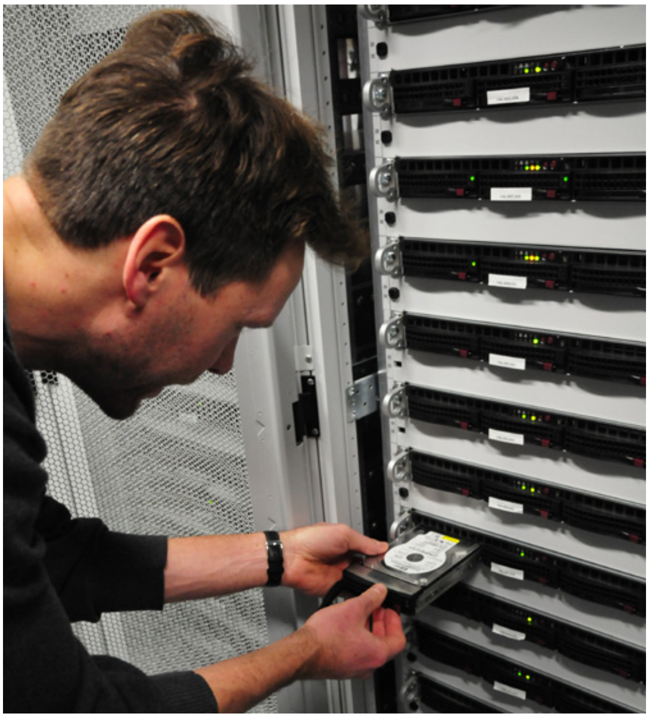


Figure 39. A member of the Grid Computing Group replaces a harddisk in one of the Tier-1 storage modules.

The BiG Grid infrastructure itself is a distributed system comprising resources at Nikhef, SURFsara, University of Groningen, Philips Research on the High-Tech Campus in Eindhoven, as well as 12 dedicated 'life science grid' nodes. Approximately half of the throughput-oriented data processing facility, is housed at Nikhef and is seamlessly integrated in both the national and global grid infrastructure. The infrastructure at Nikhef specifically caters for data-intensive computation, serving, besides the LHC communities, next-generation sequencing, medical imaging research, structural chemistry, molecular simulation and earth science research. Working on the frontier of e-Infrastructure for science offers an excellent basis for joint development projects with all Dutch universities. Through internships at Nikhef and Masters' projects, a new generation of (applied) ICT professionals have contributed to the e-Infrastructure and to solving the data management challenges of the LHC. At the same time these challenges have extended the envelope of existing training and ensured new ideas are effectively disseminated in Dutch industry. Nikhef works with PDEng students of the Software Technology programme (OOTI) at the Technical University of Eindhoven (TU/e), with the System and Network Engineering (SNE) master of the Institute of Informatics at the University of Amsterdam, and has a continuing collaboration with the Amsterdam University of Applied Sciences (HvA) on systems engineering and security software projects. One of us has also been appointed as e-science integrator at the recently founded *Netherlands eScience Center* (NLeSC), which supports and reinforces multidisciplinary and data-intensive research through creative and innovative use of ICT in all its manifestations.

Figure 40. The AMS-02 detector mounted on the International Space Station ISS. The CO_2-cooling system for the silicon trackers of this experiment was developed by Nikhef in collaboration with NLR.

Links through FEL-like research facilities
In structural biology, (bio-)molecular physics and condensed matter physics research spatially and temporally coherent X-rays are in high demand. These are delivered at a rapidly increasing number of facilities worldwide, including the European XFEL (Germany), SwissFEL (Switzerland), FERMI@Elettra (Italy), LCLS (USA) and SACLA (Japan). High energy time-resolved electron diffraction with 10–100 femtosecond electron pulses, requiring significantly smaller scale infrastructure, offers complementary research possibilities. The high acceleration gradient X-band technology, in development at CERN for future high-energy electron-positron colliders, allows for a considerable reduction in size and cost of future research infrastructure in these fields. By optimizing design with ultra-precise dynamic alignment (Nikhef) and state-of-the-art electron sources (TU/e), the undulators can be made significantly shorter. This, in combination with the generation of higher harmonics in lasers (VU), can guarantee a high degree of reproducibility.

The detector and data acquisition systems for the experiments at FELs are very demanding due to the requirement in area, resolution, multiplicity and sensitivity to different types of particles. The same holds for the data analysis and interpretation. These are exactly the areas in which our community has much to offer.

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 in order 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. For ASML, the World's largest manufacturer of semiconductor lithography equipment, Nikhef is investigating CO_2 cooling applications with very accurate temperature stabilisation.

A few years ago 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. RASNIK systems are nowadays in use for monitoring movements in tunnels, shopping malls, bridges and driven piles. 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 to be deployed over a few hundred square kilometres for oil exploration. This is likely to result in another start-up.

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 eight AMS-IX locations, as measured in number of customers (about 120 companies, representing a sizeable portion of the total public and private peering traffic in the Netherlands). The societal impact of this activity is unquestionable. The success of the Internet really took off, after CERN developed the WWW concept in the early nineties with the future LHC community in mind. The first three websites in the World were: www.cern.ch, www.slac.stanford.edu and www.nikhef.nl (in that order). One of the WWW cofounders still vividly remembers one of the very first innovative web applications: the *square root facility* launched by Nikhef collaborator Willem van Leeuwen. This illustrates that the enormous and often unexpected societal impact of the spin-off of curiosity driven research is hard to anticipate. The experience of providing a reliable data centre for AMS-IX at Nikhef has paid off enormously in setting up and running of the Dutch Tier-1 grid computing facility.

Figure 41. 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.

Links to medical industry

The same pixel technology as marketed by our ASI start-up is being developed together with Philips to yield 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. With X-ray energy information specific features, such as K-edge imaging of iodine or gadolinium, when using contrast agents and the disentangling of density and elemental composition in radiotherapy, can be significantly enhanced.

Currently, PET camera count rates are limited by the coincidence logic that triggers the read-out. With the modern SiPMT technology, developed by Philips, a triggerless readout, with timestamp in combination with large scale parallel processing of the data will result in a higher statistical accuracy, whereas the better timing resolution translates in more precise 3D position information on the point of interaction in the detectors and hence better sensitivity and image contrast. This is relevant for dynamic metabolic studies (diagnostics), for which count rate capability is a key issue and for particle therapy (verification dose delivery), where sensitivity and image contrast are essential.

In particle radiotherapy of cancer conventional X-ray CT-imaging is often a limiting factor for the quality of the treatment. This applies in particular to cases with complex geometries (*e.g.* head and neck region) and/or with image distortions due to metal parts (like hip prosthesis and teeth implants) in the patient's body. These distortions are caused by the physics of X-ray absorption in matter. Imaging proton energy loss does not suffer from these problems but has a lower contrast than X-ray imaging. The detector technology developed for the LHC experiments is a key factor for a successful proton imaging system. By combining the information from both imaging modalities the quality of the information needed for treatment planning in radiotherapy can be strongly improved, thus leading to a better outcome.

Industrial networking

Besides the aforementioned activities, Nikhef interfaces in many more ways with the 'outside world'. Our industrial liaison officer informs Dutch industrial parties about upcoming CERN-tenders. He has also 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. The link to CERN and for that matter other accelerator laboratories provided by Nikhef generates pay-back to Dutch society in terms of industrial contracts that not only yield financial advantages but also, due to their high-tech nature, broaden the Dutch technology base. Furthermore, 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, most notably PANalytical.

“Topsectoren”

A few years ago, the Dutch government identified nine areas (*‘topsectoren’*) in which the Netherlands excels. *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

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applies equally well to our own activities in experimental astroparticle and 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.

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. 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.

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8 Subfield Classification

According to the FOM subfield classification system, the proposed programme mainly (more than 90%) belongs to the subfield of *Subatomic Physics*.

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4. *The ATLAS Experiment at the CERN Large Hadron Collider*, Aad *et al.* (ATLAS Collaboration), JINST **3** (2008) S08003.
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6. *Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s}$=7 TeV*, Aad *et al.* (ATLAS Collaboration), Eur. Phys. J. **C71** (2011) 1577.
7. *Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment*, CERN-LHCC-2011-012 ; LHCC-I-020;
   Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment, CERN-LHCC-2012-022 ; LHCC-I-023.
8. *The LHCb Detector at the LHC*, Alves *et al.* (LHCb Collaboration), JINST **3** (2008) S08005.
9. Several publications with first results on CP Violation, *e.g.*:
   - *First evidence of direct CP violation in charmless two-body decays of B^0_s mesons*, Aaij *et al.* (LHCb collaboration), Phys. Rev. Lett. **108** (2012) 201601.
   - *Observation of CP violation in $B^\pm \to DK^\pm$ decays*, Aaij *et al.* (LHCb collaboration), Phys. Lett. **B713** (2012) 351.
   - *First evidence of direct CP violation in charmless two-body decays of B_s mesons*, Aaij *et al.* (LHCb collaboration), Phys.Rev.Lett. **108** (2012) 201610.
   - *Evidence for CP violation in time integrated $D \to h^+h^-$ decay rates*, Aaij *et al.* (LHCb collaboration), Phys. Rev. Lett. **108** (2012) 111602.
10. *Measurement of the CP violating phase φs in the decay $B^0_s \to J/\psi\, \varphi$*, Aaij *et al.* [LHCb collaboration), Phys. Rev. Lett. **108** (2012) 101803.
11. *First evidence of the $B^0_s \to \mu^+\mu^-$ decay*, Aaij *et al.* (LHCb collaboration), Phys. Rev. Lett. **110** (2013) 021801.
12. *Probing New Physics via the $B^0_s \to \mu^+\mu^-$ Effective Lifetime*, De Bruyn *et al.*, Phys. Rev. Lett. **109** (2012) 041801.
13. *Implications of LHCb measurements and future prospects*, Aaij *et al.* (LHCb collaboration), J. High Energy Phys. **02** (2013) 041.
14. *Letter of Intent for the LHCb Upgrade*, CERN-LHCC-2011-001.
15. *The ALICE experiment at the CERN LHC*, Aamodt *et al.* (ALICE Collaboration), JINST **3** (2008) S08002.
16. *Elliptic Flow: A Brief Review*, Snellings, New J.Phys. **13** (2011) 055008.
17. *Collective phenomena in non-central nuclear collisions*, Voloshin, Poskanzer and Snellings, Landolt-Börnstein, Relativistic Heavy Ion Physics, Vol. **1/23** (Springer-Verlag, Berlin) 2010.
18. *Flow analysis with cumulants: Direct calculations*, Bilandzic, Snellings and Voloshin, Phys. Rev. **C83** (2010) 044913.
19. *Elliptic flow of charged particles in Pb-Pb collisions in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*, Aamodt *et al.* (ALICE Collaboration), Phys. Rev. Lett. **105** (2010) 252302.
20. *Letter of Intent for the Upgrade of the ALICE Experiment*, CERN-LHCC-2012-012 ; LHCC-I-022.

Five key papers per experiment with significant Nikhef contributions

ATLAS

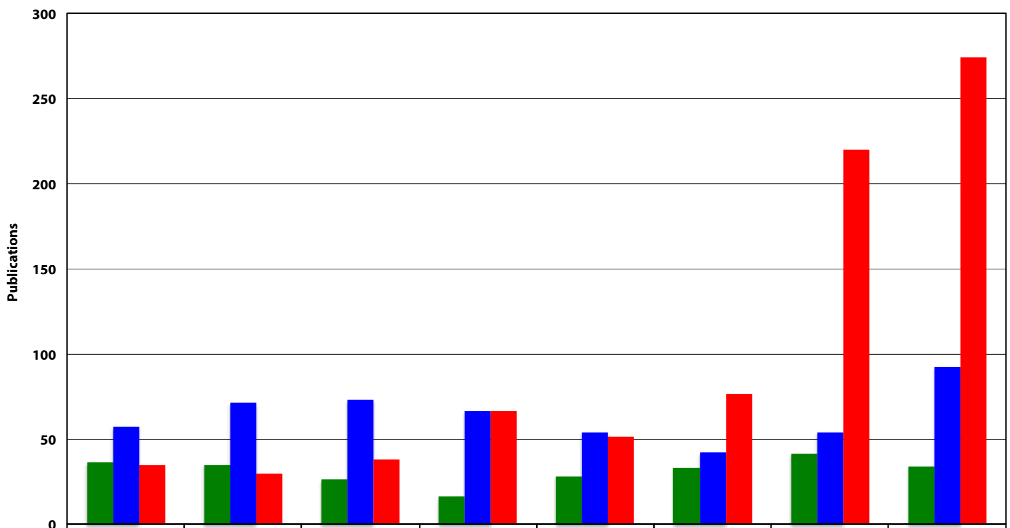
1. *Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC*, Aad *et al.* (ATLAS collaboration), Phys. Lett. **B716** (2012) 1.
2. *Search for the Higgs boson in the $H\rightarrow WW^{(*)}\rightarrow l\nu l\nu$ decay channel in pp collision data at $\sqrt{s}$=7 TeV with the ATLAS detector*, Aad *et al.* (ATLAS collaboration), Phys. Rev Lett. **108** (2012) 111802.
3. *Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s}$=7 TeV,* Aad *et al.* (ATLAS collaboration), Eur.Phys.J. **C71** (2011) 1577.
4. *Measurement of the t-channel single top-quark production cross section in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector,* Aad *et al.* (ATLAS collaboration), Phys. Lett. **B717** (2012) 330.
5. *Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s}$=7 TeV proton-proton collisions*, Aad *et al.* (ATLAS collaboration), Phys.Lett. **B710** (2012) 67.

LHCb

1. *First evidence of the decay $B_s\rightarrow\mu^+\mu^-$*, Aaij *et al*. (LHCb collab.), Phys.Rev.Lett. **110** (2013) 021801.
2. *Probing New Physics via $B_s\rightarrow\mu^+\mu^-$ Effective Lifetime*, De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Pellegrino, Tuning, Phys.Rev.Lett. **109** (2012) 041801.
3. *Branching Ratio Measurements of B_s Decays*, De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Tuning, Phys.Rev. **D86** (2012) 014027.
4. *Measurement of the CP-violating phase φ_s in the decay $B_s^0\rightarrow J/\psi\,\varphi$*, Aaij *et al.* (LHCb collab.), Phys.Rev.Lett. **108** (2012) 101803.
5. *Determination of f_s/f_d for 7 TeV pp collisions and a measurement of the branching function of the decay $B_d\rightarrow D^-K^+$*, Aaij *et al.* (LHCb collab.), Phys.Rev.Lett. **107** (2011) 211801.

ALICE

1. *Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV*, Aamodt *et al.* (ALICE Collaboration), Phys. Rev.Lett. **105** (2010) 252302.
2. *Higher harmonic anisotropic flow measurements of charged particles in Pb–Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV*, Aamodt *et al.* (ALICE Collaboration), Phys.Rev.Lett. **107** (2011) 032301.
3. *Suppression of Charged Particle Production at Large Transverse Momentum in Central Pb–Pb Collisions at $\sqrt{s_{NN}}$=2.76*, Aamodt *et al.* (ALICE Collaboration), Phys.Lett. **B696** (2011) 30.
4. *Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV*, Abelev *et al.* (ALICE Collaboration), Phys.Rev.Lett. **110** (2013) 012301.
5. *Suppression of high transverse momentum D mesons in central Pb-Pb collisions at $\sqrt{s_{NN}}$==2.76 TeV*, Abelev *et al.* (ALICE Collaboration), JHEP **1209** (2012) 112.



	2005	2006	2007	2008	2009	2010	2011	2012
ALICE	36	35	26	16	28	33	41	34
LHCb	57	71	73	66	54	42	54	92
ATLAS	35	30	38	66	51	76	220	274

Figure 42. Number of refereed papers of: ATLAS+DØ, LHCb+BaBar and ALICE+STAR, showing the steep increase of publications at the start of the LHC. The DØ experiment stopped in 2011, the BaBar experiment in 2008, while the Nikhef involvement in STAR ended in 2011. Source: Nikhef Annual Reports 2005-2012.

Appendix. Mini CVs of the Applicants

Prof.dr. F. Linde

Career history

2004–present	Nikhef director, the Netherlands
1993–present	Professor University of Amsterdam (UvA), the Netherlands
1995–2000	CERN staff, Switzerland
1991–1993	CERN Fellow, Switzerland
1988–1991	Research physicist Carnegie Mellon University (CMU), USA
1984–1988	PhD student FOM/Nikhef, USA & the Netherlands: PhD degree, Leiden, the Netherlands
1983–1984	PhD student State University Utrecht (RUU), the Netherlands
1976–1983	Master degree, Utrecht (cum laude), the Netherlands

International experience

- Member of international scientific advisory committees: LNF and LNGS in Italy, LAL in France, ANTARES, KM3NeT and Virgo experiments
- Member of evaluation panels: DESY, Helmholtz, BMBF, INFN
- Member of the "Preparatory Group" organizing the work for the first "European strategy for particle physics" adopted by CERN council in its Lisbon meeting in 2006
- Member of the "European Committee for Future Accelerators" (ECFA) and of the "Astroparticle Physics European Coordination" (ApPEC) committee
- Co-author of the action plan for physics in the Netherlands *"Fysica voor de toekomst – Toekomst voor de fysica"*

International conferences

Frequently enrolled in conference/workshop related committees.

Grants and Prizes

- Physicaprijs 2013
- CERN Fellowship

Prof.dr.ir. P. J. de Jong

Career history

2013–present	Co-program leader of FOM ATLAS program
2012–present	Professor University of Amsterdam (UvA), the Netherlands
2009–2012	Professor at University of Amsterdam with chair sponsored by *"het Genootschap tot bevordering van natuur-, genees- en heelkunde"*
2004–2012	Nikhef staff member
1999–2003	Nikhef staff with FOM *"Springplankplaats"* position
1996–1998	CERN Fellow, Switzerland
1993–1996	Postdoctoral research associate, Massachusetts Institute of Technology, USA
1988–1993	PhD student FOM/Nikhef
1983–1988	Student Technische Natuurkunde, University of Twente, the Netherlands

International experience

- Member of Particle Data Group, co-author Review of Particle Physics
- Co-convener ATLAS supersymmetry group, 2008-2010
- Co-organizer workshops with LHC Physics Center at CERN, LHC experiments and theorists
- ATLAS contact person for "Implications of the LHC" workshop
- Co-organizer ICHEP 2002
- Member LEP electroweak working group, member LEP W-physics coordination group
- Co-convener L3 W-physics group
- Active contributions to experiments at DESY (Hamburg), Fermilab (Chicago), CERN (Geneva)

Grants and Prizes
- NWO VICI grant
- FOM Springplankplaats
- CERN Fellowship

Prof.dr. N. de Groot

Career history

2013–present	Co-program leader of FOM ATLAS program
2004–present	Professor of physics, Radboud University Nijmegen, the Netherlands
2004–present	Chairman Dutch Research School Subatomic Physics (OSAF)
2009–2012	Director of the school of mathematics, physics & astronomy, Radboud University Nijmegen, the Netherlands
2003–2004	Deputy division head, Rutherford Appleton Laboratory, UK
2001–2004	Senior research physicist, Rutherford Appleton Laboratory, UK
1999–2001	Lecturer, University of Bristol, UK
1996–1998	Postdoctoral researcher, Stanford Linear Accelerator Center, USA
1993–1996	Postdoctoral researcher, Nikhef-K laboratory, NL (based at CERN)
1988–1992	PhD student UvA & FOM/Nikhef, degree march 1993
1983–1988	Master degree physics UvA, the Netherlands

International experience
- Member of international steering committee Institute of Particle Physics Phenomenology, Durham, UK
- Reviewer of rolling grant for Science and Technology Funding Council, UK
- Member programme advisory panel physics, VUB, Brussels, Belgium
- Spokesperson BaBar UK 2003–2004
- Referee for several grant rounds for PPARC (UK), NWO and FOM
- Member PPARC advisory panel on future linear accelerators

International schools and conferences
- Organiser BND 2011 school in the Netherlands
- Organiser IMAPP symposium 2006
- Member programme committee BND schools for subatomic physics
- Member organisation committee two CKM workshops

Prof.dr. M. Merk

Career history

2005–present	Program leader B-physics, Nikhef, the Netherlands
2004–present	Professor VU University Amsterdam (VU), the Netherlands
2000–2005	Senior Research Physicist at Nikhef, the Netherlands
1997–2000	KNAW Fellow, Utrecht University, the Netherlands
1994–1997	Postdoctoral research physicist at Nikhef, the Netherlands
1991–1994	Postdoctoral research physicist at Carnegie Mellon University (CMU), USA
1987–1991	PhD student, Radboud University Nijmegen, the Netherlands

International Experience
- Member of ECFA plenary
- Dutch representative ACCU
- Reviewer for Swiss National Science Foundation (SNSF), Research Foundation Flanders (FWO)
- Membership LHCb collaboration board, technical board, computing board
- Main authorship of parts of LHCb Technical Proposal, Technical Design Report, Upgrade Letter of Intent
- Chair Nikhef scientific advisory board

International Conferences
Frequent enrolled as speaker/organizer of conferences/workshops

Prof.dr. A. Pellegrino

Career history

2012–present	Professor University of Groningen (RuG), the Netherlands
2005–present	Deputy Program leader B-physics, Nikhef, the Netherlands
2001–present	Senior Research Physicist at Nikhef, the Netherlands
2000–2001	Tenure-track physicist at Argonne National Lab, USA
1999–2000	Postdoctoral research physicist at Argonne National Lab, USA
1996–1999	Fellow, DESY Hamburg, Germany
1991–1996	PhD student, Nikhef and VU, Amsterdam, the Netherlands

International experience
- Project leader LHCb Outer Tracker (2002–2010)
- Membership LHCb technical board and search committee
- Coordinator Structure Function and Electroweak Analysis group (ZEUS collaboration, 2000–2001)
- Reviewer for Centro Nacional de Física de Partículas, Astropartículas y Nuclear (CPAN, Spain)
- Reviewer of several experimental projects by international collaborations
- Frequent participation at conferences/workshops as speaker/organizer
- Referee for physics journals

Grants and Prizes
- Awarded in 2011 "High-Level Senior Expert" one-year grant by CPAN
- Awarded in 2012 "Special Visiting Grant" three-years grant by Brazilian Ministry of Science, Research and Innovation (programme *"Ciencia sem fronteiras"*)
- Awarded CERN Scientific Associateship (2007–2009)

Prof.dr. R.J.M. Snellings

Career history

2013–present	Program leader of FOM ALICE program
2012–present	Director master program Particle Physics, Utrecht University, the Netherlands
2010–present	Vice-chair institute for subatomic physics, Utrecht University, the Netherlands
2010–present	Professor Utrecht University, the Netherlands
2001–2010	Nikhef staff member
2000–2001	Lawrence Berkeley National Laboratory staff, USA
1998–2000	Lawrence Berkeley National Laboratory postdoctoral fellow, USA
1993–1998	PhD student FOM/Utrecht, the Netherlands

International experience
- Member Nuclear Physics European Collaboration Committee (NuPECC) for the Netherlands (since 2012)
- Physics board member ALICE collaboration (since 2011)
- Co-convener ALICE Correlations and Fluctuations physics working group (since 2012)
- Co-convener STAR spectra physics working group
- Reviewer for applications in the field of Nuclear Science for the Department of Energy (DOE), USA
- Reviewer for applications in the field of Physical Science and Engineering for the National Science Centre, Poland
- Co-organizer workshops at CERN & ECT*, Trento, Italy

Grants and Prizes
- NWO VICI grant (2011)
- NWO VIDI grant (2005)
- FOM Springplankplaats (2001)

Prof.dr. T. Peitzmann

Career history

2002–present	Professor of Physics, Utrecht University, the Netherlands
2002–present	Director, Institute for Subatomic Physics, Utrecht University
2002–2013	Program leader of FOM ALICE program
2002	Staff Scientist, GSI Helmholtzzentrum, Darmstadt, Germany
1998–2002	Associate Professor (Hochschuldozent), University. of Münster, Germany
1992–1998	Assistant Professor (Wissenschaftlicher Assistent), University of Münster, Germany
1990–1992	Postdoctoral Researcher, University of Münster, Germany
1987–1990	PhD student, University of Münster (partially based at CERN), PhD degree (summa cum laude)
1980–1987	Master (Diplom) in Physics, University of Münster, Germany

International experience

- Upgrade Coordinator of the ALICE experiment
- Member of the Governing Board of Funding Agency FOM
- Member of Programme Advisory Committee of GSI
- Member of the ESF expert committee NUPECC (until 2012)
- Member of ECFA plenary
- Member of the Advisory Committee for Physics and Astronomy of the Dutch Academy of Science (2005–2008)
- Physics Working Group Convenor in the STAR Experiment (2005–2007)
- Project Leader of the lead glass photon detector of WA98 (1992–1997)

International conferences

- Member of the International Advisory Committee of Quark Matter Conferences
- Co-organizer of international conferences (*e.g.* Hot Quarks, High-p_T physics at the LHC)