2.1 ATLAS
Harvesting LHC Run 1

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When Peter Higgs witnessed the discovery announcement of the Higgs boson on 4 July 2012, he proclaimed that he had never thought that this discovery would have happened in his lifetime. For particle physics this timely discovery of the Higgs boson opens a new window on fundamental physics that was never experimentally accessible before.

Nikhef students, postdocs and staff played an important role in various analyses in ATLAS that led to the discovery of the new particle, and have now embarked on a series of comprehensive studies that will allow to characterise the Higgs sector of nature in detail.

Harvesting 'Run 1'
'Run 1' of the LHC formally ended on 14 February 2013 when the beams were dumped and the LHC went into a two-year shutdown. The collected luminosity of 5 fb^{-1} at 7 TeV and 20 fb^{-1} at 8 TeV exceeded initial expectations, proved that the ATLAS detector is operating well, and led to a wealth of physics results. Nikhef contributes to the muon system, the silicon strip detector and to the trigger and readout system and takes part in their operation. Physics-wise we concentrate on top quark physics, Higgs physics, and searches for physics beyond the Standard Model. On these topics five Nikhef students have graduated in 2014, three of which earned the distinction cum laude, and one thesis was awarded the ATLAS thesis award.

Is the new boson the Standard Model Higgs boson?
The full 2011-2012 dataset is more than double the size of the discovery sample, which allowed us to study the properties of the new particle in more detail.

After an extensive recalibration of the ATLAS detector the measurements of the reconstructed mass of decays of Z boson pairs and photon pairs have been used to measure the mass of the Higgs boson with a precision of about 3 permille. This outstanding result, based on a detailed understanding of the detector performance after only two years of operation, is a crucial input to all theoretical calculations on Higgs physics.

Last year's determination of the observed Higgs boson being a 0^+ spin-parity state exploited the angular correlations between the decay products in the *WW* and *ZZ* decay channels. This analysis has been continued in a new form that also sets limits on the observed Higgs boson being an admixture of two CP eigenstates. Nikhef continues a leading role in this new analysis in the *WW* decay channel, as well as in the *WW/ZZ* combination effort.

The proverbial smoking gun in the assessment whether the observed particle is the Standard Model Higgs boson, or one of the Higgs bosons in a more elaborate theory, is the pattern of coupling strengths of the discovered particle to all other elementary particles. These coupling strengths can be inferred from Higgs decay rates to these particles, or production rates from these particles. Due to an unexpected gift of Nature —a Higgs boson with a mass of 125 GeV— the Higgs decay rate to many fermions and gauge bosons turn out to be large enough to be measurable at the LHC. These measurements will be the basis of a detailed 'fingerprinting' of the Higgs sector in the next decade.

Currently, seven of these Higgs coupling strengths are experimentally accessible. The most recently added measurement is the coupling of the Higgs to top quarks, through a search for Higgs bosons produced in association with a pair of top quarks, where the Higgs boson decays to a pair of *b*-quarks. The identification of these events is challenging due to large backgrounds from top-quark pair production, and has long been considered an analysis for the far future. Recent progress in measurements of top backgrounds and multivariate techniques, in which Nikhef has played a crucial role, has allowed a first constraint on $t\bar{t}H(b\bar{b})$ production this year. Furthermore we have contributed to the evidence for Higgs production through the vector boson fusion process in the *WW* decay channel.

We also studied the frequency of double parton interactions as a potential background to double Higgs production. These analyses will become particularly relevant for Run 2 of the LHC.

Searches for physics beyond the Standard Model
The discovery of the Higgs boson confirmed that its mass, 125.36 GeV, is of the order of the electroweak scale. However, in the Standard Model the mass of the Higgs boson is subject to quantum corrections that are many orders of magnitude larger, unless the parameters of the theory are highly fine-tuned. An important question is therefore: Why is the observed Higgs boson so light? One possible answer is that new physics regulates these quantum corrections so that the Higgs boson can be light without a delicate fine-tuning of theory parameters. One of these regulating theories is supersymmetry, which could explain the low mass of the Higgs boson, if the new particles predicted by supersymmetry are not too heavy.

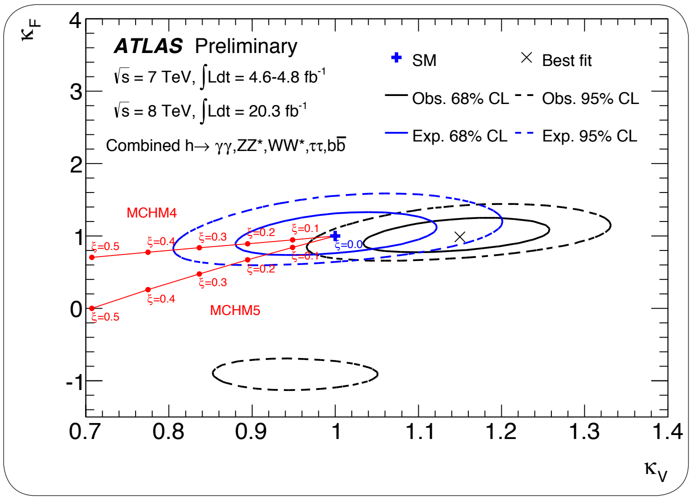

Figure 1. Measurement of Higgs coupling strengths to fermions (K_F) and gauge bosons (K_V) relative to the Standard Model expectation. The black contours indicate the allowed regions from a fit to all ATLAS Higgs decay rate measurements. In the context of a Minimal Composite Higgs Model, an extension of the Standard Model that predicts that the Higgs boson and fermions are composite particles, these couplings can deviate from the Standard Model values along the trajectories that are shown in red, depending on an assumed compositeness energy scale that is related to the parameter ξ. The data constrain ξ<0.15 (0.20) for MCHM type 4 (5) at 95% C.L., corresponding to a lower limit on the compositeness scale of 640 (550) GeV.

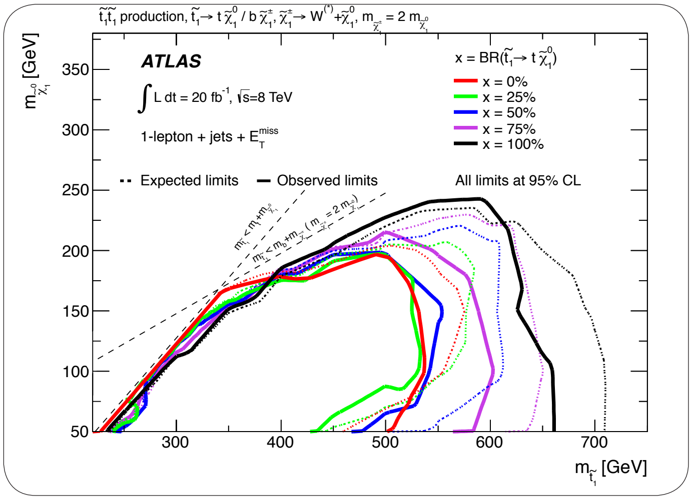

Figure 2. Result of the search in Run 1 data for pair production of supersymmetric top quark partners ($\tilde{t}_1$), where each $\tilde{t}_1$ can decay to either a top quark and a neutralino ($\tilde{\chi}_1^0$) or a b-quark and a chargino ($\tilde{\chi}_1^{\pm}$). Shown are the excluded masses of top quark partners ($m_{\tilde{t}_1}$) and neutralinos ($m_{\tilde{\chi}_1^0}$) obtained from the non-observation of such decays in Run 1 data. The excluded masses depend on the assumed branching fraction of top partners to neutralinos, and this dependence is illustrated by the contours in the various colours.

The Higgs discovery and the measured Higgs mass might be seen as new guiding principles to search for new physics. New physics that regulates the Higgs boson mass will on the one hand modify measurable properties of the observable Higgs boson, and on the other hand introduce additional heavy particles, *e.g.* superpartners, that might be produced and detected in the LHC.

Following the first strategy, a new Nikhef-led study tests the measured Higgs coupling strengths against predictions of a wide range new physics theories. Even with the present precision of coupling measurements this reinterpretation of ATLAS measurements constrains parameters of supersymmetric theories, portal dark matter models, composite Higgs models (see Fig. 1) and many more models.

Nikhef also actively participates in a number of dedicated direct searches for supersymmetric partner particles. These searches include final states with zero leptons, supersymmetric particles of the third generation, and general searches for supersymmetry. Figure 2 shows exclusion limits of an analysis with a strong Nikhef contribution on a model in which pairs of stops —the partners of top quarks— are pair-produced, and subsequently decay to a quark and either a neutralino or a chargino. Run 1 has set significant limits on supersymmetry; in constrained models squarks and gluinos below approximately 1.5 TeV are excluded. The 2015 LHC run at full energy will put supersymmetry to further stringent tests.

One of the fundamental questions of particle physics is whether elementary particles such as leptons and quarks are really elementary. To test this hypothesis we look for excited states of these particles that decay to three or more normal leptons. So far no evidence of such decays was found above background level. Nikhef also has a research line looking for lepton-flavour violating processes in tau decays. While experimentally very challenging, an observation would be indicative of new physics.

Top quark physics

The abundant production of top quarks at the LHC allows to perform precision tests of physics involving interactions with this heaviest quark found so far in nature. Top quarks almost always decay to a *b*-quark and a *W*-boson. No charge-parity (CP) violation is expected in this decay in the Standard Model. However, anomalous tensor couplings in this decay vertex may take complex values and introduce CP-violation that would manifest itself in modified decay distributions of polarised top quarks. We have analysed angular distributions of decay products of top quarks that originate in polarised form in electroweak production processes to set limits on CP violation in tensor couplings in the *Wtb* vertex.

Future physics in ATLAS

In the 2013-2014 LHC shutdown (LS1) the LHC machine was preparing for future operation at higher energies. Simultaneously ATLAS was upgrading the detector for running in 2015 and beyond at nominal LHC luminosity. Nikhef is involved in various projects in LS1. The ATLAS pixel detector is extended with an additional layer of silicon sensors, the insertable B-layer (IBL), closer to the interaction point. Nikhef has constructed a cooling plant for the IBL, based on evaporative CO_2 cooling. The plant has been delivered to CERN and has been commissioned in 2014. The cosmic events taken at the end of 2014 demonstrate a fully operational inner detector, now including the IBL, as shown in Fig. 3.

The level-1 trigger will have to cope with significantly larger collision rates in Run 2, which implies that it will have to become smarter. ATLAS tries to achieve this in the form of a topological trigger that will enable ATLAS to trigger at the first level on smart combinations of objects. Nikhef develops 'momentum imbalance' reconstruction algorithms to be run on the new topological trigger in order to improve searches for supersymmetry. Nikhef has also constructed an electronics board that will enable the feeding of muon detector information to the topological trigger. We have also adapted the MROD read-out modules of the muon system to deal with the higher data rate. In Run 2, which will last from 2015 to 2018, the LHC is expected to deliver some 150 fb^{-1} at a centre-of-mass energy of at least 13 TeV. The higher energy will be very beneficial for searches for new massive particles.

After Run 2, the LHC will shut down for an extended period again (LS2) in order to upgrade the LHC injectors and prepare for luminosities exceeding the design luminosity. ATLAS will replace a layer of endcap muon chambers with a layer of new chambers to improve triggering on muons in the forward region. Nikhef is involved in the readout of the new system, which will be based on a new design with high-speed optical links, configurable in a flexible way. This will also be used for the trigger system of the electromagnetic calorimeter and serve as a prototype for a readout of the full detector after future upgrades. The recently awarded NWO National Roadmap grant will fund the Nikhef contributions to ATLAS upgrades from 2014 until 2021.

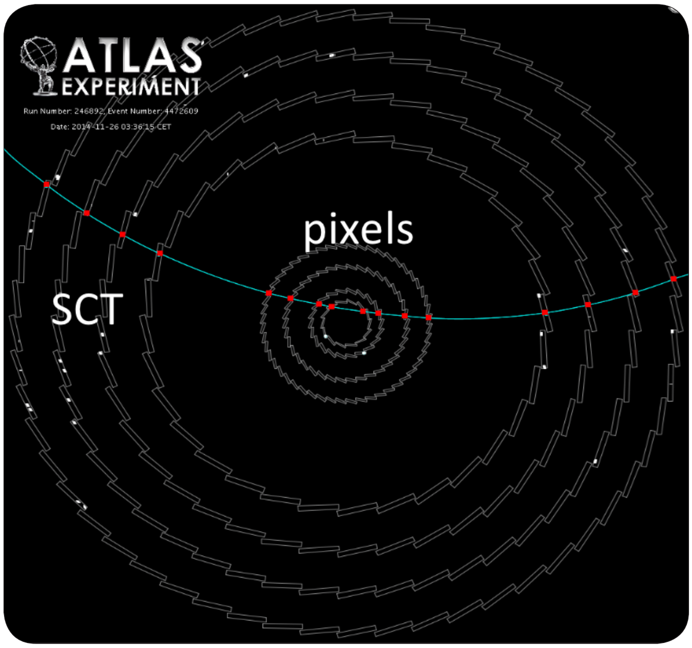

Figure 3. A cosmic muon passing through the ATLAS inner detector, including the newly installed Insertable B-layer (IBL), which is shown as the innermost ring.

The European Strategy for Particle Physics has prioritised the full exploitation of the LHC up to a delivered luminosity of 3000 fb^{-1}. This is achievable with a significant upgrade of the accelerator and the detectors after 2023, in a project known as the high-luminosity LHC (HL-LHC). The Nikhef ATLAS group has participated in physics studies for the HL-LHC upgrade, in particular in searches for supersymmetry, Higgs production and *WW* scattering. The HL-LHC will demand a new inner detector (ITk) for ATLAS, based on all-silicon sensors, able to stand the higher instantaneous and integrated luminosity and the corresponding radiation dose. Nikhef is involved in design studies and simulation, as well as in the design of an endcap strip detector, with the aim to construct one complete endcap detector at Nikhef. In November the ATLAS ITk upgrade project was formally kicked off, where Nikhef has expressed interest, among others, to design and assemble an ITk endcap.