Project description – High Energy Particle Physics at LHC Run 2

Proposal[1] for a "NFR Forskerprosjekt" within "CERN-related" program 2016-2019

Farid Ould-Saada et al., 9 September 2015

1. Relevance relative to the call for proposals

The follow-up of the current High Energy Particle Physics (HEPP) Project closely follows the call for proposals to ensure optimal scientific use of Norway's CERN membership and the investments made through participation in the ATLAS experiment at the Large Hadron Collider (LHC). The "HEPP at LHC Run 2" proposal aims mainly to

- Cover Norway's share of the operation and maintenance costs for the ATLAS detector,
- Support data preparation and analysis and an ambitious physics research program,
- Contribute to funding and operation of the Norwegian part of the computing infrastructure, part of the Worldwide LHC Computing Grid (WLCG), in collaboration with the Nordic eInfrastructure Collaboration (NeIC), Sigma2 and USIT (Oslo University IT centre),
- Take part in the upgrade of the ATLAS detector through R&D within silicon sensors for the new inner tracker, as a necessary preparation for the infrastructure application aimed at covering the full upgrade program.

High Energy Particle Physics recently extended the frontiers of knowledge by discovering the last element of the Standard Model (SM) of elementary particles, the Higgs boson. Some of the most advanced technology in existence was required to achieve this feat: the LHC itself - the world's highest energy particle accelerator - and the largest particle detectors ever built, one of them being the ATLAS experiment. The next LHC run will achieve higher energies and collision rates and will precisely measure the properties of the Higgs boson - and explore a completely new energy regime, where "New Physics" can be expected to be discovered.

Our strong team of experts in physics analysis, computing, detector technology and statistics, proposes a way to refine the ATLAS detector, strengthen the computing infrastructure and tools, and innovate in analysis methods, in order to take part in this revolution in understanding the basic laws of nature. We aim to educate tomorrow's experts - masters and PhD students – and share the excitement, data and discoveries with students and the public.

2. Aspects relating to the research project

The project objectives are already described in the grant application form.

Background and status of knowledge

The Standard Model (SM) describes interactions between quarks and leptons (Figure 1). At high energies, it unifies electromagnetism, a macroscopic force carried by the massless photon, and the weak force, a microscopic force carried by heavy W and Z bosons. The

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resulting electroweak symmetry is broken at low energies to give the W, Z, and all matter particles masses. The Universe is suffused with an invisible scalar field, which acts on particles and provide them with mass. The Higgs particle observed in 2012 by ATLAS and CMS at LHC is the manifestation of this Higgs field. Englert and Higgs, two of the people behind the mechanism of electroweak spontaneous symmetry breaking, were awarded the 2013 physics Nobel Prize. The discovery of the Higgs particle has been a “global effort leading to a global success”, in the words of the CERN DG, Rolf Heuer. “The results today are only possible due to the extraordinary performance of the accelerators, the experiments and the Grid infrastructure”. Further data will allow in-depth investigation of the Higgs boson's properties and thereby of the origin of mass. Are there more Higgs bosons?

Despite the success of the SM it is not the ultimate theory of Nature. It does not account for dark matter or dark energy, and does not incorporate gravity. Higher symmetries than those defining the SM would be needed to relate leptons and quarks (Grand Unified Theories, GUT) and matter particles and force carriers (Supersymmetry, SUSY). Superstring theories, where particles correspond to vibrations of extended “strings”, in 10 space dimensions, are the current candidates for the ultimate unified theory. SUSY predicts five Higgs bosons and proposes a good candidate for Dark Matter observed in the Universe.

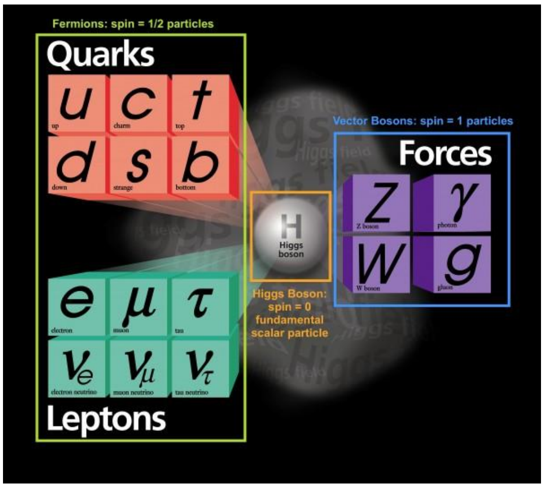

Figure 1 - Standard Model particles.

Are there hidden space dimensions, which would allow gravity-related phenomena, such as the production of microscopic black holes and gravitons, to occur?

In addition to the discovery and study of the Higgs boson we exploited the ATLAS detector at the LHC to look for a large spectrum of new phenomena. Despite enormous gains in mass reach in Run 1, there is no direct evidence for new physics yet. However, we have collected only a few per cent of the data planned for the full LHC program and already in 2016 the doubling of the collision energy could yield some surprises.

Current status[2]

The LHC collider, the ATLAS detector, the software and computing infrastructure and the data analysis framework are ready to tackle the challenge.

LHC plans. The current LHC Schedule is full of promises:

- 2010-2012 – Run 1 delivered ~5 fb^{-1} of data at 7 TeV energy and ~25 fb^{-1} at 8 TeV
- 2013-2014 – LHC Shutdown 1 (LS1) prepared the machine for nearly design energy (13 TeV) and nominal luminosity
- 2015-2018 – Run 2 at 13 TeV where 100 fb^{-1} of data are expected
- 2019-2020 – Injector and LHC Phase 1 upgrades to ultimate luminosity 2.2 x nominal.
- 2021-2023 – Run 3 at 14 TeV to accumulate few 100 fb^{-1}, closing Phase 1 of LHC
- 2024-2026 – Phase 2 Ultimate luminosity Super LHC (SLHC)
- 2027-2035 – Run 4 (27-29), LS4 (30), Run5 (31-35) to collect 3000 fb^{-1} at 14 TeV.

[2] Contributions made by Norwegian HEPP members can be found in the CVs attached to this application.

ATLAS and the HEPP project. LHC and ATLAS have so far been hugely successful. The discovery of the Higgs particle and the scrutinised search for new physics in all possible corners are the highlights so far.

Detector. We played a crucial role in designing, constructing and operating the ATLAS detector, with emphasis on the Semi-Conductor Tracker (SCT), the main contribution being to deliver 300 detector modules. A necessary condition to discover the Higgs particle is the excellent operation of the tracker. LS1 was devoted to detector consolidation, installation of a new innermost pixel layer for the tracker, the Insertable B-layer (IBL), and other detector consolidation. In the context of the IBL, we delivered readout flexes installed in the final system and together with SINTEF we participated in the development and testing of radiation-hard silicon pixel detectors using the 3D sensor technology. This is one of the sensor technologies that will be developed further for use in the new all-silicon Inner Tracker (ITk), which will be installed during the final upgrade to high-luminosity of the LHC taking place in 2024-2025.

Computing and Software. Our key contribution is to develop and deploy Grid middleware and software and to set up the WLCG distributed computing infrastructure necessary to exploit the large amount of data produced by LHC. The NorduGrid Advanced Resource Connector (ARC) is deployed by many large-scale distributed computing infrastructures, including the Nordic NeIC, the European Grid Infrastructure (EGI) and the WLCG. ARC has been used by the LHC experiments for more than 10 years and is a highly successful and adaptable distributed computing platform. ARC serves as a job and data management middle layer without the need for computing nodes to interact with the outside world. This makes it ideally suited for use with HPC systems, which traditionally are in highly secure environments with no inbound connectivity.

The ARC Control Tower (aCT)[3] is a workload management system that handles all compute jobs from ATLAS on ARC enabled resources. The lightweight, non-intrusive design of both ARC and aCT makes it possible to set up a working environment for running compute jobs on almost any HPC cluster. This allows ATLAS to take advantage of advanced scheduling techniques like “backfilling”, increasing the amount of available computing resources and limiting the necessity to acquire dedicated resources for LHC computing. ARC and aCT also provide a gateway to the volunteer computing project, ATLAS@home, which allows the public to run ATLAS simulation tasks on their home PCs.

We have also made very significant contributions to offline software. The Derivation Framework, to be used during Run 2 to produce the ATLAS analysis formats, was largely designed and implemented by us. Significant contributions to the performance of the event reconstruction were made - these are essential to obtain the best possible physics results and realistic systematic uncertainties. Contributions were made to the simulation, reconstruction and pixel data acquisition software of the IBL pixel layer, and to combined performance of physics objects reconstruction for Run 2.

Physics. As of September 2015, ATLAS published more than 460 publications in refereed journals; we made direct contributions to ~10% of these. The physics publications cover measurements of SM processes, including the discovery and measurements of the Higgs

[3] ARC Control Tower - A Flexible Generic Distributed Job Management Framework, J. Phys.: Conf. Ser., 2015.

boson, and an extensive search for new physics phenomena. Run 1 datasets are still being analysed to make precise measurements.
The discovery of the Higgs boson at a mass of 125.5 GeV was made in 2012 by ATLAS[4] and CMS. Properties such as spin (0) and parity (+) are now established.
We made important contributions to the di-photon and tau-lepton pair decay modes of the Higgs boson as well as to the combination of ATLAS Higgs results. A key issue is the understanding of more abundant SM "background" processes to which many students dedicated large parts of their theses. A recent combination of ATLAS and CMS provides the best precision to-date on its production and decay and on how it interacts with particles. All of the measured properties are consistent with the predictions of the Standard Model. We reconstructed b-quark particles and searched for rare decays of B-mesons. These decays are sensitive to new physics at a higher energy scale and complement the direct searches at the LHC energy scale. We searched for signs of new physics in final states with electrons, muons and taus and set severe constraints on possible scenarios: (i) supersymmetric particles, including setting the first limits at hadron colliders on sleptons; (ii) new charged and neutral heavy gauge bosons, which would mediate new interactions and thus facilitate unification of fundamental forces; and (iii) extra space dimensions through the graviton, the hypothetical mediator of gravity, or microscopic black holes. The experimental contributions are complemented by theoretical calculations and predictions, especially for the electroweak symmetry-breaking sector and dark matter.

Education and Outreach. The objective to educate many students in physics, computing and technology is met. In the 4-year period 2012-2015 the number of PhD (Master) students is 13 (12), to be compared to 15 (30) in the previous 6-year period 2006-2011. Some efforts went into explaining the Higgs mechanism and mass generation, as well as new physics concepts to the general public. We developed the *Z-path*, a powerful and popular educational resource allowing high-school students to learn about particle physics and search for new phenomena using real LHC collision data. The ambition to bring to the "classroom" important LHC discoveries is realized using the recent discovery of the Higgs boson. Invariant mass is successfully mastered to measure properties of known particles and discover new ones[5].

Approaches, hypotheses and choice of method

This project aims to collect and exploit 13 TeV data until end of 2018, prepare the ATLAS detector to tackle even higher collision rates and energies during the long shutdown (LS2) taking place in 2019-2020, adapt the computing infrastructure accordingly, and improve the analysis and statistical techniques. HEPP theoretical particle and astroparticle physicists in Oslo, Bergen and Trondheim are part of this application or collaborating through common projects, thus creating some synergy in result interpretation and widening the scope for new physics searches.

Our strategy will be to play a key role in the following areas further discussed below:

- Duty towards the collaboration

- ATLAS Maintenance and Operations is a necessary service work and the HEPP team has the overall expertise to perform the tasks.

[4] A particle consistent with the Higgs Boson observed with the ATLAS Detector, Science 338 (2012) 1576.
[5] Bringing LHC data into the Classroom, PoS ICHEP2012 (2013) 559; ATLAS W and Z path physics and the Z path measurement, EPJ Web of Conf. 71 (2014); Sharing ATLAS data and research with young students, Procs ICHEP 2014

- Distributed Computing, Data Management and Analysis, Data Model. Expertise acquired in Grid middleware and data handling through various Grid project is an important asset. Oslo hosts several researchers, including the core of the data management system, funded outside the HEPP project.
- ATLAS upgrades and R&D within the Inner tracking detector. This is a natural continuation of the excellent contribution to the ATLAS SCT, IBL and pixel R&D.
  - Exploitation
- Combined Performance studies
- Focused physics program based on a few final states and conducted within physics groups
- Phenomenology and result interpretation through synergy with theoreticians
- Education, communication and outreach.

Commitments to ATLAS duties (maintenance and operations, detector upgrade, and computing and software) are necessary investments to best exploit the rich LHC physics program.

3. The project plan, project management, organisation and cooperation

The project period, the progress plan, and the activities and milestones are provided in the online application form. In this section, we detail the project plan. We first describe the strategy behind our research plan, present the project activities, the expertise and personnel required to carry out the tasks as well as the management and organization of the project, and finally go through the projects and applications of interest for cooperation.

Project Plan

Computing and Software. With the restart of the experimental program at higher collision energies and luminosities, data rates will increase dramatically, giving new posing to distributed computing. Continued contributions to the WLCG infrastructure and related developments is not only necessary to fulfil the requirements for participation in LHC experiments, but also provides experience at the forefront of computing technology. The requirements imposed on software during the third LHC run will be as stringent as those on the computing resources. The data throughput that will have to be achieved exceeds anything that our community has managed to date. Such performance can only be attained by combining a number of techniques - multi-threading and parallel processing of events - as well as novel algorithms and optimisation of existing software. Inner detector track reconstruction is the most important part of the offline software in this regard due to the very high density of tracks that will arise from Run 3 collisions. We will contribute to the development of high-throughput inner tracking software during Run 2 and the second long shutdown, ensuring that the components are in place for the start of Run 3.

We worked extensively on ATLAS software and computing developments during LS1. We will continue to contribute to the maintenance and development of these components, as well to ATLAS distributed computing operations. We will continue to develop and operate the ARC Control Tower, allowing further integration of non-traditional resources such as large HPC centres and volunteer computing into the ATLAS production system. We will integrate ARC and the Event Service, including enabling access to object stores. Development, maintenance and operation of the ATLAS Distributed Data Management (DDM) system, Rucio, and the further integration of Rucio and ARC (especially with regards to allowing full access to ARC caches through Rucio and extracting popularity information from ARC), will all be under our responsibility the coming years. Building on the work done on the derivation framework in LS1, the production of derived data formats using this framework will be coordinated by us, according to the requirements of the physics groups.

ATLAS detector upgrade. The coming four-year period is crucial for the detector upgrades that are foreseen for successful exploitation of the data to be collected at the collision rates foreseen during LHC Phase 2, planned to start in 2024. For the HEPP project it is crucial to strengthen the activities within the ITk, the planned new tracker. The ITk will replace the current Inner Detector, and consists of two parts, both using silicon sensor technology: the Pixels and the Strips. The R&D necessary for the ITk is now approaching its final phases. We have participated in this activity, notably in the development of novel 3D sensors, and participation in the IBL (Insertable B-Layer) and the recently approved AFP (Atlas Forward Proton) projects. Both projects employ 3D pixel sensors, and are stepping-stones for the final sensor technology to be employed by the ITk Pixels. Our contributions to these projects are within the delivery of PCB flexes and mechanical parts. A series of processing runs for 3D pixel sensors has been launched with SINTEF, with layout and geometry compatible with the requirements for the pixels for the ITk. During the fall of 2015, these sensors will be evaluated in test beams at CERN.
For meaningful contributions to the ITk, our involvement must be substantially scaled up, with investments in infrastructure items and qualified manpower. We would like to accommodate funding for one applied physicist/engineer, who, together with the existing personnel, targets his/her work to detailed planning and realisation of the infrastructure needed to contribute to the construction of the ITk. As we did for the SCT, we plan to contribute to silicon modules construction. This requires significant upgrades of existing facilities. The departments at UiO and UiB already possess cleanrooms, but the equipment to be used for module assembly and testing needs to be acquired. This includes probe stations, bonding machines, equipment for precise positioning of components, and equipment for module testing. Given the long term experience in the design of printed circuit boards on solid and flexible material, it is also likely that we will be asked to take on design and production tasks in this area.

A strategic physics exploitation plan. The strategy for both New Physics searches and Higgs and other SM measurements is

- choose a few promising final states and thus minimize the technical studies required to perform precise measurements which are sensitive to new physics
- use and further develop methods and tools to discriminate new physics from SM physics, and relate LHC results with other experiments worldwide
- make use of the WLCG infrastructure, including the Nordic Tier-1, to gain access to large amounts of real and simulated data stored worldwide.

We will search for new physics in basic final states containing at least one lepton (electron, muon or tau). The various searches with leptons present some synergy. The trigger (high p_T lepton), tracking and lepton reconstruction and identification, data-driven SM background estimations, systematic uncertainties, and the studies of SM candles (such as Z and W), are common or very similar, as are the advanced statistical techniques required to perform such analyses.

Standard Model, flavour and Higgs precision measurements. We will perform precision measurements of the Higgs boson mainly through its decay to 2 photons, 2 taus and 4 leptons, as a follow-up of the search carried out in Run 1. We will continue with studies of b hadrons[6] and with global fits of CKM matrix[7] and Wilson coefficients.

(i) Higgs decays to tau-pairs. We will continue to explore novel techniques for estimating the invariant mass of tau-pairs and use the tau-polarisation information to discriminate between Z and Higgs decays. The tau-tau final state is appropriate for spin and CP (charge conjugation and parity) measurements of the Higgs boson. In the past, we have developed a method to find the rest frame of two-body decays where not all energy is visible[8]. A feasibility study has been launched to enhance the sensitivity to forbidden decays such as Z, H to tau-mu. While accumulating data, the plan is to take an active part in the efforts to 'rediscover' the Higgs boson in the tau-tau channel, and also to look for monochromatic recoiling muons in the new data. Towards 2018-2019 sufficient amounts of data are expected to start meaningful studies of the spin and CP properties of the Higgs boson.

(ii) *Higgs decays to diphotons.* The products of branching ratio times cross section show consistency with the SM prediction for various production mechanisms[9]. These measurements will be repeated at higher energy and eventually with a larger sample in order to look for deviations that might give hints of new physics. One of the challenges of the diphoton channel is that the large background under the narrow signal peak has to be interpolated precisely and without bias from sideband measurements. A method is being studied to merge the power of the statistically limited but full simulation of the dominant SM background with very large samples of generated background events. If successful this would replace the less rigorous parameterization currently in use and allow ATLAS to control and estimate the systematic uncertainty in the signal strength for the large sample expected by the end of Run 2. These results would then be input to a wide spectrum of improved measurements and searches.

(iii) Higgs decays to 4 leptons through ZZ^*. We are investigating two new methods to improve the statistical sensitivity of the signal strength measurement for the production mechanisms vector boson fusion (VBF), Higgs-radiation of a vector boson (VH) and gluon-gluon fusion (ggF). The first method uses two-dimensional boosted decision tree (BDT) probability density functions (PDFs) that were produced with separately trained VBF and VH events and checked versus ggF events. The second method is still under investigation and employs neural network classifiers, which further improves the statistical sensitivity of signal strength measurement. Both methods are being tested using the 8 TeV Run 1 data sample before we apply them to Run 2 data. We plan to measure angular distributions with the full dataset.

Searches for new physics with lepton final states. This was our substantial physics analysis activity in Run 1 resulting in 6 PhD theses and direct contribution to 20 published papers. We will work in four main directions:

(i) Model-independent search. We will perform a model-independent study of one, two, three and four charged-lepton (electrons and muons) final states. Discriminating variables will be developed and exploited to distinguish between various models. Backgrounds will be

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6 Search for the decay $B_s^0 \to \mu\mu$ with the ATLAS detector, Phys.Lett. B713 (2012) 387-407; Determination of the ratio of b-quark fragmentation fractions fs/fd in pp collisions at $\sqrt{s}$=7 TeV with the ATLAS detector, arXiv:1507.08925.

7 Global CKM Fits with the Scan Method, Phys.Rev. D89 (2014) 033004.

8 Method to Estimate the Boson Mass and Optimise Sensitivity to Helicity correlations of $\tau^+\tau^-$ final states, JHEP01(2012)43

9 Measurement of Higgs boson production in the diphoton decay channel at 7 and 8 TeV, Phys. Rev. D90 (2014) 112015

estimated with data-driven methods. Leptonic decays of Z^0 and W will be exploited as high-statistics control channels. Models with two-leptons include high-mass resonances Z′, Z*, black holes, gravitons, as well as non-resonant excesses such as new contact interactions. Three-lepton events may stem from flavor violating resonances, such as R-parity violating SUSY decays of charginos. W' or supersymmetry may lead to final states with leptons and missing energy. Finally, massive spin zero resonances may decay via $ZZ^{(*)}$ to four leptons. Such states originate in some extensions of the SM in addition to one of the most prominent precision measurement channels for the SM Higgs boson just described above.
For all of the new physics searches with leptons, we will investigate novel techniques such as anomaly detection, which could identify non-SM physics without relying on signal MC.

(ii) Searches for SUSY and exotics with electrons and muons. We have already published many results (including 4 PhD theses) on searches for SUSY in channels with two[10] or more leptons, additional charged (W', W^*)[11] and neutral (Z',Z^*) or graviton[12] (gauge) bosons in one- and two-lepton channels, respectively. We will extend the searches with electrons and muons via the electroweak production, involving sleptons and gauginos.
Interesting hints arise from Run 1 ATLAS and CMS data, which will be explored in Run 2. In a search for narrow resonances decaying into WW, WZ, or ZZ boson pairs, an excess of events is observed at 2 TeV in the invariant mass distribution of di-jets from highly boosted W or Z. An excess of events in the same-sign dilepton channel with b-jets and missing transverse energy is observed by five separate analyses. The very first Run 2 data, collected in July 2015 were analysed by two of our students in search for W' and Z', and the results were presented at EPS-HEP 2015.

(iii) SUSY strong production with tau-leptons. We have been exploring the SUSY parameter space with relevance to astrophysics and dark matter searches. This often involves the supersymmetric partners of the tau (staus), leading to tau leptons in the final state. In order to enhance the sensitivity to SUSY it is essential to improve tau reconstruction in ATLAS, and possibly measure tau polarization. This motivates our direct involvement in the ATLAS tau performance group, which will strengthen throughout Run 2. While Run-1 search results were converted into limits, our Run-2 analyses will be optimised towards discovery.
We will continue to (a) lead the strong production search in the one-tau channel[13], (b) work on the combination of results from the one-tau, two-tau, tau+light lepton channels, and (c) interpret the results of strong production searches with taus in the context of simplified models[14] and more realistic SUSY scenarios such as the pMSSM[15]. We have made a leading contribution to the DM interpretation of ATLAS SUSY searches in the pMSSM scan, as well as in the Monte Carlo simulation of simplified models, and we will keep these commitments for Run 2.

(ii,iii) In all lepton channels (electron, muon, tau) we will extend SUSY searches to cover all relevant pMSSM phenomenologies helped by collaboration with theory and astrophysics

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[10] Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in pp collisions at $\sqrt{s}$ =8 TeV, JHEP 05 (2014) 071; Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in $\sqrt{s}$ =8 TeV pp collisions, JHEP 04 (2014) 169.

[11] Search for new particles in events with one lepton and missing transverse momentum at 8 TeV, JHEP 09 (2014) 37.

[12] Search for High-Mass Dilepton Resonances in pp Collisions at $\sqrt{s}$ = 8 TeV, Phys. Rev. D 90 (2014) 052005.

[13] Search for supersymmetry in events with large missing transverse momentum, jets, and at least one tau lepton in 20 fb^{-1} of $\sqrt{s}$ = 8 TeV proton-proton collision data, JHEP09 (2014) 103.

[14] Searches for squarks and gluinos using $\sqrt{s}$ = 8 TeV pp collisions, arXiv:1507.05525.

[15] ATLAS sensitivity to supersymmetry after LHC Run 1 - interpreted in the phenomenological MSSM, arXiv:1508.06608.

colleagues within this project. SUSY searches are interpreted for more general cases than they are optimized for, including constrained models (mSUGRA, NUHM, GMSB, …) and a 19-D scan of the pMSSM. In such scans all SUSY searches performed in our project are effectively combined.

(iv) Dark matter search in mono-W and mono Z-events. These are general DM investigations extending the search for SUSY DM. We will investigate mono-W and mono-Z production. The W' search was interpreted as mono-W and a pair of DM particles within the framework of Effective Field Theory (EFT) or contact interaction, when the mediator of the interaction between SM and DM particles is very heavy. "Simplified models" of DM production, including particles and interactions beyond the SM, provide an extension to the EFT approach. At the LHC, the kinematics of mono-X (X=jet, W, Z, H) reactions occurring via a TeV-scale mediator can differ substantially from the prediction of the contact interaction.

Synergy with Theory. There is a wide spectrum of theory activities in Norway that tie into the experimental work, allowing for productive national collaborations, strengthening both experiment and theory. The two main themes are: the exploration of the electroweak symmetry-breaking sector at the LHC, and studies to optimize searches for supersymmetry and DM.

On-going Higgs sector studies explore models that also lead to DM candidates, as well as additional CP violation effects, and how these could be experimentally searched for. The focus will mainly be on LHC searches for two Higgs doublet models and the exploration of the properties of inert Higgs doublet models. Here there is long-term collaboration between experiment and theory in Bergen to define relevant benchmark points[16].

In collaboration with experimentalists we plan a consistent analysis of mono-X searches. Within simplified model we will consider both mono-X and mediator production as well as precise measurements of W/Z production, Higgs invisible branching ratio measurements, and direct and indirect DM detection. A software package is to be developed for the analysis, which allows for the prediction of consequences for indirect DM observation. A Short Term Association (STA) with ATLAS for one or more theorists will be formed to facilitate collaboration.

We will explore supersymmetric scenarios with a gravitino LSP, where the next-to-lightest superpartner (NLSP) is metastable, leading to interesting phenomenology at colliders and in the early universe. Since the NLSP relic density depends on the properties of the NLSP and other sparticles, LHC results can be used to constrain it[17]. We plan to extend this work, with a focus on determining how and with what accuracy it will be possible to measure the relevant parameters of the NLSP after a potential discovery, or what bounds can be set otherwise. In addition, we would like to establish methods that can differentiate between a long-lived sneutrino NLSP and a stable neutralino LSP. Given the experimental expertise in tau identification, we also plan to investigate whether looking for taus from the decays of heavier sparticles into a tau sneutrino NLSP could boost sensitivity. While super weakly interacting DM cannot be detected directly, indirect detection could find its decay products if R-parity or some other stabilizing symmetry is broken, making the DM unstable. For decaying DM relating the coupling governing DM decay to the coupling governing production at colliders

[16] Probing the charged Higgs boson at the LHC in the CP-violating type-II 2HDM, JHEP1211 (2012) 011.
[17] A survey for low stau yields in the MSSM, JHEP04 (2014)053.

links LHC and indirect searches. We plan to identify classes of such models and study their phenomenology, in particular with respect to the discovery potential of the Cherenkov Telescope Array.

By using global fits of new physics models we will explore the impact of the wealth of new results from the LHC. Our participation in the GAMBIT Collaboration (a Global and Modular Beyond the Standard Model Inference Tool) aims to produce a valuable tool for joint experiment/theory studies of models across particle and astrophysics, using large scale computing. This tool will be used on Run 2 results to constrain the large parameter spaces of popular new physics scenarios such as the MSSM. Results from the LHC will also be propagated to the DarkSUSY code, which explores DM models, in the form of model limits.

Indirect searches for DM require a good understanding of particle physics-based uncertainties. We will apply LHC results to the following: improve models of cosmic ray propagation based on the "trajectory approach", reduce uncertainties on secondary production in hadron interactions by more careful modelling of these processes in Monte Carlo codes such as QGSJET-II-04, and improve on models of antideuteron formation.

Education and Outreach. The ambition to bring to the “classroom” important LHC discoveries will be carried on, building on the *Z-path* educational tool. The opportunities offered by the 13 TeV LHC era and by the CERN open data access triggered the extension of the educational material. Research projects based on large LHC data samples open new possibilities for university students and result in strong interest in related lecture courses. New features are being implemented into the *Z-path* that will serve both high school and university students, and the key concept of missing energy is also in the pipeline.

Expertise, manpower and tasks

In this section we first list the project activities and manpower needed to carry out the ambitious scientific plan, described above, in the following areas:

- *Physics analysis*, including: expertise in lepton and photon reconstruction and identification; data-driven background techniques; fluency in the use of advanced tools for statistical interpretation of data.
- *Expertise in semiconductor-based tracking hardware, software, and distributed computing.* This expertise will be crucial to achieve the commitments for the construction and installation of the new inner tracker (ITk) and to tackle the extremely challenging software and (distributed) computing tasks.

Description of project activities. The key activities for this project are:

A1: ATLAS Operations
Follow-up of the ATLAS Maintenance and Operations (M&O), including planning and execution of service work and various shifts (detector, computing and software, data preparation) to be committed.

A2: ATLAS detector Upgrade
This includes R&D in 3D pixels for the new Inner Tracker (ITk), prototyping and test beam, deployment of technology within the ATLAS Forward Proton (AFP) detector, and the operations of the newly installed Insertable B-layer (IBL).

A3: ATLAS Computing & Software. Development of software (new tracking and reconstruction techniques, multi-threading), middleware (ARC), data management (Rucio) and other computing components to match the Exascale nature and complexity of the extreme conditions prevailing at the Super LHC.

A4: Physics exploitation
This is the most important activity related to the overall goal of the project. It is split into sub-activities coordinated by physicists directly involved in the research fields. The physics research plan and the strategy behind are detailed below.
A4.1: Combined performance. Build on the expertise and achievements in hardware and software to optimise the use of physics objects, maximize efficiencies and minimise systematic uncertainties.
A4.2: Standard Model and Higgs physics. *A4.3: Supersymmetry and Dark Matter.*
A4.4: Exotic physics. *A4.5: Particle physics theory.*
A5: Management, cooperation, dissemination, education and outreach, exploitation.

The Milestones corresponding to each of the activities Ax.y are listed as Mx.y.z in the timetable of the project plan.

Manpower. The manpower contribution from the participating institutions, entered into "Funding plan" of the online form, consists of senior staff, with an important record in all aspects of research in particle physics, and PhD students. In addition we rely on excellent researchers and postdocs, financed by the RCN. For more details we refer to the CVs and information entered into the grant application form.

David Cameron is the ATLAS Distributed Computing Operations Co-coordinator, in charge of ensuring smooth operations of ATLAS Grid computing, and heavily involved in the commissioning of the new ATLAS computing systems developed during LS1 up to the final preparations for the start of Run 2. He is also a key responsible in the ATLAS@Home volunteer computing project and an active developer of the ARC middleware.

James Catmore plays a leading role in the development work for the ATLAS data derivation framework and worked on the new analysis format. He has completed the main software development optimisation of the framework. He is responsible for liaising between physics groups and ATLAS Distributed Computing with regards to storage usage. Expert in B-physics and muons, he joined the exotics group to search for new gauge bosons.

Eirik Gramstad has been part of the ATLAS train coordination team, and main responsible of the production part of the new derivation framework. He follows up the requests from the physics groups and ensures that the overall derivation production is successful. Expert in SUSY analysis and QCD background determination, with several ATLAS publications, he pursues supersymmetry searches through electroweak production of gauginos and sleptons.

Bertrand Martin is in charge of the energy calibration of hadronically decaying tau leptons for early Run-2 analyses. Expert in calorimeter operation, he is working on advanced techniques that exploit both tracking and calorimeter measurements to calibrate the energy of individual pions from tau decays. He worked on searches for squarks and gluinos with tau leptons, and made significant contributions to ATLAS Run-1 SUSY legacy papers.

Ole Røhne plays a key role in the R&D activities in Oslo, in close contact with the local engineers and technicians. He has been leading the IBL contribution, co-convening the IBL Stave working group, and responsible for delivering readout flexes. He collaborates with

SINTEF on 3D silicon sensor R&D, in view of the use of unique single-sided 3D thin silicon sensors for the ITk. He was member of the TALENT ERC Network for detector related PhDs.

Zongchang Yang is working on the study of the Higgs properties in the four leptons decay channel, based on the production mechanism specific signatures. He develops new categorization approach with advanced machine learning algorithm, which may improve the measurements in Run-2. He is also involved in 3D pixel detector R&D activities for ATLAS Phase-II upgrade, and building a pixel testing system in Bergen.

The excellent contributions to the ATLAS computing and software activities and to ARC lead to a strengthening of the HEPP project. *Jon Nilsen* (USIT and NeIC) is ARC release manager and co-developed and operates the ARC Control Tower. He helped ATLAS computing to run on Chinese HPC through the ATLAS production system. *Vincent Garonne* (ATLAS) is the Distributed Data Management (DDM) project leader. His responsibilities are the coordination of the development team (~10 persons); support of the system; and the development of the system project, called Rucio. He is responsible for the system architecture, contributing as a core developer and release coordinator of the project. *Cedric Serfon*, another Rucio key developer, also funded by ATLAS, starts 1st October 2015 for a period of 3 years.

Project management and organisation. University of Oslo (UiO) is the coordinator of the project. Partners from University of Bergen (UiB) and University College of Gjøvik (HiG)[18] are entered under the item for "Partners" in the grant application form. Confirmation letters from the three institutions are uploaded.

The management structure is chosen such as to be as efficient as possible and also to provide the least overhead in comparison with related projects.

Farid Ould-Saada (UiO) will act as *project leader (PL)* and will be supported by a *deputy (DPL)* to cover for him in case of absence and to provide a second hand in meetings nationally or internationally when needed. The PL is the entry point to both the Research Council of Norway and to the financial office at the Department of Physics. The PL will work closely with and take part in meetings of the *Norwegian CERN committee*, with the main task to report to the committee and to collaborate with the other CERN-related projects.

Anna Lipniacka (UiB) will act as DPL with further responsibility as coordinator of the Bergen HEPP team. The PL, the deputy PL and a representation from the other permanent staff will function as a "steering group" (SG). The PL and deputy will have frequent videoconference meetings. The SG will meet twice a year, and when necessary, to assess the overall progress of the project and to settle any nontrivial management issues. We will strive for consensus.

The SG will agree on the distribution of funds between the partners. A collaboration agreement (CA), regulating partners' rights and duties, will be entered into with all partners before a contract may be signed between the RCN and the coordinator.

Nomination of activity coordinators improves the functioning of the project and the communication between project members and between partners. Weekly face-to-face meetings (with videoconference possibility) allow the members to discuss progress and technical challenges. Researchers are encouraged to play leading roles and PhD students to be

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[18] We will seek collaboration with NTNU when the merger is completed at the beginning of 2016.

active in the relevant ATLAS working groups. Project members, including students, will participate intensively in "service work" related to the operation and maintenance of the experiment and computing infrastructure. PhD students are required to perform 90 working days of technical work to qualify as ATLAS authors. Some of the qualification work is directly relevant to the aims of the project and we will make full use of such synergies. We will also recruit several master students.

Collaboration. The experimental staffs at UiO and UiB are members of the ATLAS collaboration, which consists of more than 3000 physicists and students from 37 different nations, as well as Computing collaborations. The theoretical staff also have international collaborations.

The HEPP project members are part of complementary projects or applications:
- The Strategic Dark matter Initiative, involving the experimental and theoretical particle physics groups and the Institute for Theoretical Astrophysics at UiO, funds 5 PhDs and a postdoc. This presents a case for cooperation within physics analysis and interpretation of dark matter results at LHC and at other facilities, such as the Cherenkov Telescope Array.
- The RCN-funded four-year FRINATEK project "GAMBIT: a Global and Modular Beyond the Standard Model Inference Tool".
- Further developments of silicon sensors are included in AEgIS[19] and 3DMiMiC[20].
- Synergy Grid - particle physics research is a result of fruitful collaboration with NorduGrid.
- The NordForsk-funded project "ARC for eInfrastructures" starts in September 2015 and runs for 3 years. The main goal is ARC middleware maintenance and support, and the resolution of scalability issues linked with the increase usage of ARC.
- Advanced Resource Connector for Secure Data-Services Everywhere – Frinatek RCN application (May 2015) with the aim to contribute to ARC development beyond HEP.

Budget. Budget information is accounted for in the electronic application form. The funding we seek from the RCN and the breakdown among various activities is shown in Table 1. Further details about the budget and the matching funding from the participating institutions are detailed in entry "funding plan" of the online form.

The baseline budget shows an increase of order 25% (high Swiss Franc exchange rate, which went from 6.4 to 8.6, and salary increase) compared to the current project. This is essential in order to fulfil the overall goal of the program: (i) take part in a vital way in any discovery in a new energy domain, by keeping the researcher team proposed, including enough PhD students, (ii) ensure a sustained detector R&D to achieve a successful infrastructure proposal in 2016 to cover the core detector phase 2 upgrade estimated to be ~2.5 MCHF for Norway, and (iii) provide the pledged computing resources.

The computing infrastructure (Table 2) will be renewed for another period of 4 years in March 2017 and will serve for Run 2 and data analysis during the LHC shutdown 2. The cost estimate is 12 MNOK for 4 years, consisting of hardware, manpower for operation, support and maintenance at sites. We allocate 6 MNOK to the hardware investments. We expect CPU to be partly covered by the NOTUR quota, (currently 4,7 kHEP Spec 06). The project share of the operations is agreed with Sigma2 and USIT to be of order 1.44 MNOK.

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[19] Norwegian participation in the AEGIS experiment at CERN.

[20] The 3DMiMiC project is funded by RCN within the NANO2021 program.

Table 1 - Detailed budget request from research council. All figures are in 1000 NOK.

Expenditure	2016	2017	2018	2019	Total
ATLAS Maintenance & Operations	1892	1892	1892	1892	7568
ATLAS Upgrades	1131	3131	1111	1111	6484
Phase 1 - AFP prototyping: flexes, holders	70	70	50	50	240
Phase 2 - 3D pixel R&D new inner tracker	1061	3061	1061	1061	6244
Tier-1 Computing Infrastructure:	630	6630	630	630	7440
Researcher positions	5058	6243	5364	4426	21092
Travel & subsistence: Atlas, outreach, theory	2275	2275	2275	2275	9100
Options (upgrade and position co-funding)	400	900	900	2900	5100
Sensor R&D - SINTEF run, workshop	100	100	100	2100	2400
Engineer Bergen 50%		500	500	500	1500
Co-funding of positions	300	300	300	300	1200
Budget – Baseline – no options	**10548**	**20062**	**10858**	**10216**	**51684**
Budget with Options	10948	20962	11558	13116	56784

Table 2 - ATLAS Norwegian share in the Nordic Tier1. Current CPUs expire end of 2016 and disk in 2017. Tape lasts 8 years. Investments are in parentheses.

Tier 1 plan	2016	2017	2018	2019
CPU-kHS06	8,1(11,6)	10,5 (4,7)	11,5 (4,7)	12,6 (4,7)
Disk-Pbytes	0,7	0,9 (0,6)	1,0	1,1
Tape-Pbytes	1,81(1,4)	3,3 (1,4)	3,6	3,9

It is the baseline budget of 51.684 MNOK, which is entered to the online form.
In addition Table 2 features an option of 5.1 MNOK to further prepare for the infrastructure proposal we will submit in 2016. This consists mainly of a part-time engineer position to be matched by an own contribution from UiB and a second sensor run. In fact, with the latter, SINTEF would offer 3 runs in total for the price of 2, which would be very attractive and competitive. The 3D R&D is unique as SINTEF is the only producer of single-sided 3D thin silicon sensors. If successful, the current thin sensor will have an impact on the ATLAS ITk upgrade. We also include a buffer for co-funding of 2 researcher positions at a level of 20% of a full position. This could come from the RCN or universities.

4. Key perspectives and compliance with strategic documents

Compliance with strategic documents.

The experimental particle physics group of one of the partners was amongst the 15% of national physics groups that received a top ranking in the 2010 international evaluation of Norwegian basic physics research carried out by the Research Council. Our involvement in Grid development and exploitation was acknowledged. Synergy between theory and experiment is exceptional in this proposal, with a strengthening of the collaboration with the astrophysics community, following current university strategy encouraging cross-disciplinary research. The host institutions are strategically committed to supporting our activities, developing the capabilities of their mechanical workshops and electronics labs and by funding an impressive pool of PhD students, fulfilling the objective to educate tomorrow's educators, researchers and technology experts.

Relevance and benefit to society.
The project's most direct benefit to society is to generate new knowledge about our fascinating universe and how it works at a fundamental level - discoveries made today will be taught in classrooms tomorrow. It provides a training ground for a new generation of scientists who learn how to tackle difficult problems by learning new basic concepts, applying advanced analysis methods and cutting edge technology, and by exploiting the advantages of distributed computing to tackle the Exascale data era. The computing resource connector proposed by ARChestrate aims to bring LHC computing know-how into other domains of research and the public sector. Our 3D pixel project is an example of the process of technology and know-how transfer from fundamental particle physics research to society at large.

Environmental impact.
The project has no particular environmental aspects.

Ethical perspectives.
The project has no particular ethical aspects in itself. We comply with guidelines of the respective scientific communities when it comes to data ownership, authorship of scientific work and citations. The proposed activity includes working in collaboration with projects having permission from the Local Ethical Committee (REK) for their research.

Gender issues (Recruitment of women, gender balance and gender perspectives).
In Norway, Particle Physics and technology are fields with a rather low fraction of female researchers, but in line with Nordic trends in exact sciences. Our universities have been aiming at becoming a more family-friendly workplace, providing adequate parental leave and support facilities for young parents, respecting gender imbalance when hiring researchers, and aiming at a balanced work environment. In the CERN-related Norwegian community there is already a tendency towards a large fraction of young women PhD students who will naturally be given the opportunity to progress further in their academic careers and ultimately position themselves to compete for permanent academic positions.

5. Dissemination and communication of results

We refer to the electronic grant application form.

6. Additional information specifically requested in the call for proposals

No additional information is specifically requested in the call for proposals.