Research Plans of the Norwegian Particle, Astroparticle and Nuclear Physics Communities till 2025

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Abstract

Norwegian particle physics, heavy-ion physics, nuclear physics, astroparticle physics, particle, astroparticle and cosmology theory present their research program for the next period of the European Strategy Update.

1 Introduction

One of the main challenges for the European Strategy Update is that there is not yet clear experimental guidance as to the energy scale for physics beyond the Standard Model. The Norwegian community expects that the European Strategy Update for the next period will provide guidance for a European approach led by CERN, where researchers from Norway can participate at all levels. Factors that should influence the strategy include the physics potential and large investments being made for the High-Luminosity Large Hadron Collider (HL LHC) project and a strong case to pursue precision measurements of the Standard Model at current and future colliders.

Norway is one of the founding member-states of CERN. A large majority of accelerator-based particle and high-energy nuclear physics projects with Norwegian participation have been based at CERN, in order to make the best use of the CERN membership. Most recently the Norwegian community has invested heavily in the ALICE and ATLAS experiments and physics programs at the LHC and plans to participate at the same strength in the upgrades and physics exploitations of both detectors for Run 3 and beyond. We have recognized the rapidly growing challenge to process, store and analyze data from increasingly sophisticated accelerators and experiments. We plan to continue to play a leading role in the efficient and cost-effective distribution of CPU workloads, and to step up efforts to harness machine learning and the exploitation of alternate CPU architectures.

The Norwegian community also recognizes that the nature of Dark Matter (DM) is one of the most exciting open questions in physics. In addition to strong theory activities and experimental searches with the ATLAS experiment, we intend to step up our participation in the Cerenkov Telescope Array (CTA), in order to obtain privileged access to CTA data for Norwegian scientists. We are also interested in supporting proposals to intensify the search for light DM at CERN and to extend the ESS in Lund to study CP violation in the neutrino sector.

For Norwegian theory, activities at and in connection with CERN play a major role, but rather than focusing on a specific experiment, the theory community takes a broader view and combines its interest in not only particle physics but also astrophysics and cosmology in the N-PACT theory collaboration. It is important that these theory activities be given an enhanced visibility in the European Strategy Update.

The Norwegian nuclear physics community has a long history at ISOLDE at CERN. Recent energy and intensity upgrades will be exploited in studies of nuclear structure and processes relevant to nuclear astrophysics. A new storage ring at ISOLDE will offer additional unique opportunities.

Norway has ongoing R&D activities in semiconductor particle sensors and readout, high-granularity calorimetry, acceleration techniques and beam instrumentation. We are involved in several projects that leverage our expertise for medical applications. Norwegian physicists also have a natural interest in novel high-energy e^+e^- linear colliders through the connection to Bjørn Wiik, the former DESY director and professor in Bergen, who initiated the TESLA project more than 20 years ago. Although our accelerator studies have focused on novel acceleration techniques (which may become important for medical and industrial applications) and the Compact Linear Collider (CLIC), we are also in position to contribute to the International Linear Collider (ILC) and/or a future circular collider. As the Phase II upgrade of the ATLAS experiment draws to a close, our detector R&D capacity may easily be directed toward the preparation of an experiment for a new collider.

Dissemination of our results to the general public and making them, and the experimental techniques that made them possible, accessible to both high-school and university students are important priorities in Norway.

2 ATLAS physics plans

Norwegian physicists have been involved in the ATLAS experiment from the beginning and it remains to be the flagship of Norwegian experimental particle physics activities for the time frame of the European Strategy Update. Norway contributed to the construction of the SCT, the pixel detector as well as to the ATLAS combined performance. Norway also played a major role in software and middleware developments and the set-up and operation of the computing infrastructure. All Norwegian high-energy physicists have participated in a broad physics program, including studies of the Higgs boson, B meson decays and searches for new physics including supersymmetry, DM and more exotic physics scenarios. Some of these efforts have profited from a direct collaboration with theoreticians in the Nordic countries. A similar physics portfolio with the same manpower is planned for Run 3. So, on one hand we continue with precision measurements of the Higgs boson and b-flavored hadrons, on the other hand we keep searching for signatures involving leptons, photons and DM by combining analyses from ATLAS and astroparticle physics (see Section 4). In addition to physics analyses, there is a strong involvement in the ATLAS phase I and phase II upgrades (see Section 9) and in developing software solutions for the future data and analysis challenges (see Section 10).

We will continue with precision measurements of the Higgs boson in the $\gamma\gamma$, $\tau\tau$ and $ZZ^* \to 4\ell$ channels in Runs 2 and 3. Specifically for Run 3, we are interested in searches for di-Higgs production exploiting $H \to \gamma\gamma$ and searches for $H \to \mu^+\mu^-$. Our priorities in B physics focus on studies of the B_c meson with Run 2 and 3 data as well as a search for lepton flavor violation in B and B_s semileptonic electroweak penguin decays with Run 3 data. In BSM physics we will continue with searches for supersymmetric particles in leptonic final states with missing E_T. This involves direct production of sleptons including staus and charginos/neutralinos assuming that squarks and gluinos are too heavy to be produced. The search for staus necessitates the design of a specific tau trigger for Run 3 that we plan to work on.

In addition to the DM interpretation within specific SUSY models, we will perform searches for DM signals in "mono-boson" signatures like mono-Higgs, mono-Z and mono-Z' final states in simplified models with new scalars and/or gauge bosons. Common interpretation of ATLAS and other DM searches (direct, indirect) in relevant DM models will continue to be of importance for understanding the nature of DM. We plan to continue our strong involvement in searches for exotic phenomena in Run 3. These include hunting for an extended gauge sector with new resonances W', Z', resonant graviton excitations in the presence of extra dimensions, and contact interactions producing a non-resonant high-mass $\ell^+\ell^-$ excess. In final states with taus we will search for excited taus testing compositeness. The use of machine/deep learning will lead to an improved signal-to-background ratio and allow for more model-independent searches for exotic phenomena in lepton final states.

3 Plans for e^+e^- machines

Since the discovery of the Higgs particle in 2012, the focus at the LHC has shifted towards precision measurements of Higgs properties. The ultimate precision after high-luminosity running is expected to reach 2% for some Higgs couplings in a model-dependent analysis. However, e^+e^- machines will reach precisions of 1% or better for the Higgs couplings in model-independent analyses. Such a precision is necessary to uncover new physics that is expected to arise at most at the 1-10% level. Measuring many final states with high precision produces a pattern that eventually will permit a distinction among the various new physics models. Besides precision measurements, a linear collider also provides the opportunity to discover new phenomena directly since initial conditions are well defined such that energy-momentum conservation becomes an important tool in distinguishing between signal and background. Another interesting topic is the measurement of the Higgs self coupling that can be studied well at a higher-energy e^+e^- Linear Collider like CLIC or an upgraded ILC.

The Norwegian accelerator community has been active in the design of CLIC since 2005 (see section 8). Detector studies for linear colliders have been performed in Norway since 2003. Therefore, Norway is prepared and interested in participating in further developments of the CLIC technology as well as the implementation of the project itself, both on the accelerator and detector side. The project has a cost estimate, which makes it worth pursuing with high priority and a physics potential that is well aligned with the future interests of the Norwegian community to explore the SM in e^+e^- collisions. In addition, the linac technology is potentially of strategic interest for future national accelerators, albeit for other purposes than particle physics. The potential to establish a linear collider infrastructure at CERN with CLIC is of great strategic interest for Europe in the long term as novel accelerator technologies are currently the most promising and potentially affordable ones for much higher energies than even a full blown 3 TeV CLIC can provide.

The development of the ILC in Japan is also of significant interest. Even though the initial energy is not sufficient for top production, the project can be implemented by around 2030 and is expandable with international effort to higher energies, hopefully sooner rather than later. There is a clear potential for detailed Higgs studies that can provide a gateway to new physics already running at 250 GeV. Similar remarks as in the previous paragraph can be made concerning much longer-term energy upgraded e^+e^- linear colliders with novel accelerator technologies. Bergen is already a member of the SiD collaboration participating in the design and R&D of the analog hadron calorimeter. Bergen has proposed hexagonal tiles, which match the layout of the silicon pixels of the electromagnetic silicon tungsten calorimeter, and started R&D of them, see section 9. In the case that ILC is being implemented we favor an "ILC platform" at CERN for accelerator and detector contributions from Europe and Norway.

4 Experimental astroparticle physics plans

Experimental astroparticle research is relatively new in Norway while theoretical work has been ongoing for some time (see section 5). The experimental activities have focussed on the CTA experiment. Since 2012, Norway has participated in the CTA preparatory phase through the University of Bergen, funded by a pilot Dark Matter Research Center financed by the Bergen Research Foundation. The University of Oslo joined CTA in 2014, and activities are currently funded by the University of Oslo. Presently, scientists (both theorists and experimentalists) from the Universities of Bergen, Trondheim and Oslo are participating in CTA. In the future we would like to strengthen the astroparticle activity further, by both increasing our participation in CTA as well as embarking on neutrino research through ESSnuSB at ESS.

The experimental activities include analysis and responsibilities within the Key Science Projects (KSP), in particular to search for monochromatic gamma rays from DM annihilations in the Galactic Center. In the past some experimentalists have also worked over many years on the camera test facility and verification project. In the future they would like to continue with the activities within the KSPs, extend analyses related to new LHC searches and explore synergies with the Astrophysics Department at the University of Oslo. However, they plan to shift the camera test facility work towards supporting the CTA Science Data Center and distributed computing, where they can also benefit from the LHC experience. For future upgrades of CTA there may be very interesting detector R&D on e.g. SiPM, which may of interest in particular for the University of Bergen.

Now is an excellent time for extending the Norwegian astroparticle activities since the CTA construction is advancing. The program benefits from the experience in the ATLAS experiment. A CTA membership and close Norwegian collaboration are important pillars of a future strategy to form a Norwegian center for DM research. It is also important to secure the privileged access to the CTA data, influence on the CTA scientific policies, CTA Key Science Projects and the disposal of observation time.

In conjunction with the neutron spallation production at the European Spallation Source (ESS) in Lund, a very intense and cost-effective neutrino beam can be realized (ESSnuSB), which would allow leptonic CP violation to be measured at the second neutrino oscillation maximum. Norwegian physicists will contribute to the sensitivity studies, especially in connection with the use of superfine-grain scintillation detectors as active target for future neutrino experiments (see section 9).

5 Theory plans

Theoretical physics is an important and independent science driver, relying on experimental results and observations to help theory building and in return providing crucial input to experiments through explicit predictions, search strategies, and proposals for new experiments. Activities at and in connection with CERN play a major role, but rather than focusing on one specific experiment, theorists have the possibility of taking a broader view combining not only particle physics data but also astrophysical and cosmological observations. In Europe, this includes activities at ESA and ESO as well as DM and neutrino detectors. Another important factor is the flexibility to quickly turn to new directions where a breakthrough occurs. Enhanced visibility of theoretical research activities in the European Strategy Update is desirable, also in dialogue with national funding bodies. The Norwegian community in particle, astroparticle, and cosmology theory (N-PACT) is coalescing and is represented here in a single section. A new networking activity has been initiated, connecting all six institutions where theory activities currently exist. As the result of a recent generational turnover, the majority of the network members are newly appointed staff at the six institutions and are of relatively young (age $< 50\,$y). The network is working towards net growth, as well as increasing Norway's participation in CERN theory activities and the Norwegian quota there. To be successful, we see a need for funding opportunities for theory activities distinct from experiments, mirroring the role played by the Theoretical Physics Division at CERN.

The N-PACT community has a strong interest in **QCD** matter in extreme conditions. The physics of the quark-gluon plasma (QGP) at high temperatures is probed at the LHC, and complementary experiments are performed at the RHIC at BNL and possibly in the future at an electron-ion collider (EIC). The community is strongly involved in modeling and guiding these experiments. Particular activities include the study of hard probes in the QGP, such as jets and heavy quark-antiquark bound states (quarkonium), as well as questions related to the initial stages, onset of hydrodynamics and collectivity in small systems.

A unifying element among this research is the need to understand the dynamical evolution of strongly interacting quantum systems from first principles. The community collaborates on large-scale numerical simulations (lattice QCD) and is working on advanced statistical analysis tools (e.g. machine learning) to extract real-time dynamics from such computations. As similar tools are used in the analysis of experimental data, rich collaboration opportunities are foreseen.

In the lower energy front, the community is active in the study of the QCD phase diagram and the properties of ultradense baryonic matter. Efforts are made to constrain properties of high-density QCD matter with a combination of QCD calculations, accelerator experiments and using astrophysical observations including X-ray observations of neutron stars and gravitational waves.

The **phenomenology of physics beyond the Standard Model** (BSM) remains of great interest due to unsolved issues like baryogenesis, the hierarchy problem, and the origin of Dark Matter. One area of focus is supersymmetry, whose phenomenology is comprehensively explored using different probes such as the LHC, DM searches and cosmological observations. Future efforts are foreseen to place increased emphasis on the potential of future colliders and on machine learning techniques, utilizing synergies with the corresponding efforts of the experimental groups. Furthermore, we will continue studies of how to implement realistic CP -violating scenarios in an extended scalar sector and also how DM can be accommodated. The development of **software tools** for particle and astroparticle physics has become a central contribution by theory activities in Norway, in particular through involvement in DarkSUSY and GAMBIT. These activities will be continued long-term, with major new versions of both software packages foreseen. Within GAMBIT focus will be on the DarkBit sub-package for DM calculations and on ColliderBit, improving the utilization of LHC results in global fits through recasting experimental analyses and improved simulation of LHC events. For DarkSUSY, the focus will be on implementing new DM model classes and on calculating observables that complement those relevant for classical WIMP searches.

The **physics of the very early Universe** is the subject of intense observational and theoretical development. Phenomena arising near the QCD and electroweak scales are directly probed and constrained by LHC experiments, while BSM physics leading to baryogenesis, DM production and inflation is also tested by observations of the cosmic microwave background and gravitational waves. The N-PACT community includes members of the ESA/NASA LISA mission, who focused in particular on the computation of gravitational wave signatures from primordial phase transitions and inflation. Detection of phase transitions is in turn directly connected to models of (electroweak) baryogenesis and DM-genesis and also points towards QCD in extreme conditions and compact stars. Inflation model building and the computation of tell-tale signatures as well as quantum field theoretical considerations in curved backgrounds may be connected to generalized models of gravity and non-standard cosmological models.

Dark Matter model building has long focused on naturalness arguments, explaining also a clear experimental bias in favor of WIMP searches. More recently, partially triggered by the fact that no undisputed DM signals have been observed in traditional searches, these efforts have diversified on both the theoretical and the experimental side. The Norwegian DM theory community is a good example of this. While there is a traditionally strong effort on WIMP signatures, more recently there have been significant model-building and interpretation activities connected to DM models testable with cosmological observations. These activities are to be expanded, including the identification of promising new experimental directions and the re-interpretation of existing data.

Considering cosmological observables is one of the most fascinating new avenues to identify the impact of the particle nature of DM, because it offers tests of the DM nature fully independent of traditional DM searches. At early times, the impact of DM particles could be visible in the distribution of light elements created during big bang nucleosynthesis or, slightly later, in the anisotropy spectrum of the cosmic microwave background. At later times, DM self-interactions may affect cosmological structure formation, or models with strongly enhanced annihilation rates may change the expansion rate of the Universe.

Charged **cosmic rays** are protons and nuclei hitting the Earth with energies up to 10^{20} eV, i.e., with center-of-mass energies far beyond those reached at the LHC. During propagation cosmic rays interact with gas and background photons, producing secondary particles like photons, neutrinos and antimatter. Therefore, a "multi-messenger" approach can be used to identify the sources of cosmic rays, combining, e.g., information from the photon and neutrino channel. At the same time, these secondaries are a background for indirect DM searches. Therefore, a better understanding of cosmic ray physics will lead also to more effective DM searches.

6 ALICE physics plans

During the upcoming LHC running periods, ALICE will aim for a precision characterization of the hot QGP phase, exploiting its superior capability in identifying particles at low and intermediate transverse momenta and utilizing rare signals in particular in the heavy flavor sector.

A potential novel QGP signature in the LHC energy regime is charmonium production by recombination. Run 1 and 2 data have revealed a complex modification pattern for heavy quarkonia in nuclear collisions, challenging the pictures of sequential melting of bound states in a hot medium and of simple Cold Nuclear Matter effects such as initial-state gluon shadowing and nuclear absorption. Differential high-precision studies, utilizing the full capabilities of the ALICE detector, are needed to gain a consistent understanding of those phenomena.

The focus of the Norwegian ALICE groups so far has focussed on a wide selection of probes, including charmonia (J/ψ) and open charm (D-mesons). Taking advantage of increased statistics offered by the increased luminosity during Run3, the Norwegian ALICE groups will concentrate on rare tomographic probes that involve heavy quarks produced during the earliest collision stages and that experience the entire system evolution. The charmonium study is already identified as one of the pillars of the long-term ALICE physics program, and it will provide a joint focus for the Norwegian physics analysis activities. The increased luminosity in Run 3 will make bottonium final states (Υ family) accessible with high statistics and these will also be a key topic for the future Norwegian physics analyses.

Heavy quarks, in particular in the form of vector mesons, can also be produced in photonuclear processes mediated by the strong electromagnetic fields produced by the relativistic ions. This production can happen in ultra-peripheral collisions, where the nuclei do not overlap and no hadronic interactions are possible. The production of heavy vector mesons in these collisions is expected to probe the nuclear parton distribution functions in nuclei. Photoproduction of heavy vector mesons also has been observed in semi-central collisions where the nuclei partially overlap. In certain regions of phase space photoproduction, rather than hadroproduction, is the dominant production mechanism. Although a complete theoretical understanding is still lacking, it is possible that these photoproduced vector mesons could probe the quark gluon plasma. The Norwegian groups have made significant contributions to these studies and plan to continue with this activity, which will benefit from the increased luminosities in Run 3.

In addition to heavy quarks, Norwegian physicists maintain an interest in other probes, including jets and jet modification, collective flow, and bulk observables such as transverse energy and particle spectra. The above studies will be performed primarily on data from $Pb - Pb$ collisions, but $p - Pb$ collisions are indispensable as reference data.

7 Nuclear physics plans

The ion beam facility ISOLDE at CERN is an important facility for the low-energy nuclear physics community in Norway. The intensity and energy upgrade of the accelerator infrastructure at CERN will provide an increase in the driver beam energy and intensity at ISOLDE. This will make it possible for ISOLDE to deliver more intense beams of short-lived isotopes. Furthermore, it provides novel opportunities for experiments in which techniques developed for stable beam experiments can be used. The Oslo group is planning experiments related to nuclear astrophysics exploring shape co-existence far from stability. The community in Norway, therefore, plans to continue to be an active member of the ISOLDE collaboration. To enable a full exploitation of the experimental possibilities at ISOLDE, the three technical upgrades will be pursued. First, the establishment of two new target stations and a new high-resolution mass spectrometer will create a higher number of shifts to ISOLDE users, higher beam intensity and a wider range of beam species. This will permit the exploration of a larger range of physics cases and study systematics. Second, the completion of phase 3 of HIE-ISOLDE will permit fine tuning of the post-accelerated beam energy and will produce higher maximum beam energy. This is important for studies of both resonances and reactions. Third, the future installation of the ISOLDE storage ring for exotic beams produced at ISOLDE offers unique opportunities, related to life time studies in an environment closer to that in stellar environments since the storage ring can store fully stripped radioactive isotopes.

8 Accelerator physics plans

Accelerator physics and technology R&D is vital to ensure the continuity of high-energy and/or high-luminosity particle physics, because the frontiers are set by the available accelerator technology. The main parameters and the technology choice for the next machine are not made yet, since there is currently no guidance on energy scales for new physics and since it is not yet decided whether new energy frontier machines will be built in China or Japan. The Norwegian accelerator activities, centered at the University of Oslo, reflect this by covering several topics: designs of linear colliders, research into novel accelerator technology and advanced accelerator instrumentation. Norway will therefore be in a position to participate in the scientific discussions and strategies about the next machine and to contribute to the design and construction of the next machine (ensuring educational opportunities and industrial return) regardless of its parameters. National expertise in accelerator R&D also would be important if Norway were to build compact research accelerators nationally. The CERN-based projects CLIC and AWAKE are providing a good training ground for Norwegian accelerator physicists.

Norway participates in the CERN accelerator physics studies for future colliders. The main effort is towards high-gradient and beam dynamics for CLIC. Much of the techniques and studies for CLIC are applicable for the ILC as well. There is also a limited beam-dynamics activity towards LHC and HL-LHC, applicable for the future circular collider studies as well. Norway is thus positioned to contribute also to future circular machines if implemented.

Novel accelerator technology, including plasma-based technology, promises to make more compact particle accelerators. Norway is part of the AWAKE plasma acceleration experiment at CERN, focusing on numerical simulations of beam quality preservation in beam-plasma interactions. It not clear today that these technologies can reliably accelerate low emittance e^+e^- beams, or deliver sufficient power efficiency and hence luminosities, for a general purpose e^+e^- collider. However, the promise for reduced footprint and cost applies as well to compact linacs for industrial research and medical applications, indicating that research for novel technologies needs to be pursued further.

Norway is delivering the beam profile monitors for the ESS, which will be the world's most intense proton beam. This R&D project gives Norway experience with both advanced imaging and commissioning of high-intensity beams in general, important for contributions to future high-luminosity machines.

Norwegian physicists have co-signed an expression of interest to establish a new electron beam facility at CERN that is partly motivated by the lack of any direct experimental evidence for DM. Such a facility would allow CERN both to expand its research into future accelerator technology and to greatly extend the search for DM. A low-current 4-16 GeV electron beam hitting a thin target followed by a detector of modest proportions (LDMX) could give several orders of magnitude better sensitivity to sub-GeV DM coupling to electrons than any existing or planned experiment.

9 Instrumentation and detector R&D plans

Many of the present detector R&D activities are hugely benefiting from the recently established project, NorLHC, that ensures funding for establishing infrastructure and enables Norwegian participation in the upgrade programs of the ALICE and ATLAS experiments. Participation in delivering detector components and other infrastructure for these upgrades will form a major part of the instrumentation activities in the period up to 2025.

Through collaboration with SINTEF the development of silicon sensors for particle detection has a long history in Norway. Recent activities include the delivery of a novel large area strip detector for AEGIS and the development of 3D pixel sensors with several productions of prototypes.

Sensors from a recent 3D production have been mounted with the prototype readout chip for the pixel part of the ATLAS Inner Tracker (ITk). Preliminary beam tests are promising, and a new run is being launched with sensors that can be mounted on the final readout chip. Bergen also participates in the RD53 collaboration for developing, testing and debugging these readout chips. Submission of the final chip is expected to occur in the middle of 2019. The ATLAS groups in Oslo and Bergen have detailed plans for complete pixel module production for the ITk. A significant is build up in Bergen and Oslo to accomplish this taskThis includes the installation of mounting jigs, bonding facilities, probe stations and equipment for thermal cycling.

A former student from Bergen started with growing large-area diamond sensors at the Bergen physics institute. First evaluations, which have been performed by members of the RD42 collaboration, show rather promising results. Future work will be pursued within RD42, where Bergen is now a member. The longer-term plan is to build radiation/beam monitors for the ATLAS experiment, where diamond sensors are ideal due to their extreme radiation hardness.

The ALICE collaboration is preparing an upgrade of its detector to be installed during the LS2 shutdown. The main objective is to increase the readout capabilities, allowing readout and recording of Pb–Pb minimum bias events at rates in excess of 50 kHz, which is the expected Pb–Pb interaction rate at the LHC after LS2. This increase in readout speed, together with the deployment of a new data acquisition system with continuous readout, will imply an enhancement by two orders of magnitude in the collectible minimum-bias events. A key component of the LS2 upgrade program is the replacement of the current Inner Tracking System (ITS) with a new one (ITS2) that has improved vertexing and tracking performance. The new ITS consists of seven approximately cylindrical detector layers based on CMOS Monolithic Active Pixel Sensors (MAPS) with the sensor matrix and readout integrated in a single chip, named ALPIDE (ALice PIxel DEtector). It is designed with CMOS amplifier circuitry and covers a 10 m^2 area with about 12.5 billion pixels. The Norwegian groups in ALICE are contributing actively in this development.

Physicists in Bergen have a long standing expertise in calorimetry. Presently, they are involved in the ATLAS TileCal as well as calorimeter R&D for the SiD (CLICdp) detector at the ILC (CLIC). They participate in studies to track down the origin of the observed light losses in scintillator tile readout chain of the ATLAS TileCal. They also perform R&D of the scintillator tiles with SiPM readout as an alternative method. The plan for the next five years is to participate in the phase I upgrade and prepare for the phase II upgrade. The R&D for the SiD analog hadron calorimeter presently focuses on a performance study of hexagonal-shaped tiles with respect to square tiles read out with SiPMs. Bergen has proposed hexagonal-shaped tiles since they match the silicon pixel geometry in the ECAL and yield a better signal-to-background ratio as less tiles are summed up in a shower. In addition to bench tests, simulations will be performed. The plan for the next five years depends upon approval or decline of the ILC. If ILC is approved, physicists in Bergen will help with the design and construction of the analog hadron calorimeter after finishing off any left-over R&D. If the ILC is not approved then the focus will shift towards the design and construction of a calorimeter for a CLIC detector.

During recent years, R&D towards medical applications of silicon sensors has also taken place, notably through the 3DMiMiC project, where ultrathin radiation hard X-ray transmissions monitors have been successfully developed, as well as silicon 3D-microdosimeters. Work on the microdosimeters will continue during the next few years, until a full evaluation of the dosimeters has been completed. In the context of hadron therapy, a high granularity tracking calorimeter is also being developed. The purpose of such a device would be to provide online dose plan verification. The plan is to insert also ALPIDE sensors as active elements in the calorimeter.

The feasibility studies for a long baseline neutrino experiment (ESSnuSB) at ESS involves several detector R&D projects. The near detector will be a fine grained tracker in conjunction with a kiloton water Cherenkov detector. The work on the fine grained tracker follows closely ongoing developments of the near detector upgrade at T2HK, where a larger prototype was tested already at CERN for which data analyses are still ongoing. The far detector in ESSnuSB will be a 500 kt water Cherenkov detector located in the Garpenberg mine in Sweden. All detector studies will be carried out over the next years as part of the ESSnuSB INFRADEV-1 Design Study and hopefully be followed by a Preparatory Phase resulting in a Technical Design Report in 2024.

10 Computing and software plans

Members of the particle physics community in Oslo and Bergen are heavily involved with many aspects of ATLAS and ALICE computing, respectively. The CPU, disk and tape resources provided by the Norwegian contribution to the Nordic Tier-1 facility for LHC are expected to roughly double in the period 2018–2022 in order to cope with increased demands of the experiments.

The migration of the ATLAS core software over the next few years from a multi-processing to a multi-threaded model will allow ATLAS to exploit more effectively modern computing resources where the number of cores per CPU is rapidly increasing without a corresponding increase in memory. The use of machine learning is being explored over many diverse areas of software and computing and it is important to identify the areas where real benefits can be achieved. In recent years disk space has been the most critical resource for the experiments and it is vital to work on changes in workflows or policies that can lead to a more effective use of disk space.

The Oslo group leads the NorduGrid collaboration that produces the ARC middleware, which is becoming the middleware of choice in grid sites in many parts of the world. The ARC middleware is especially useful in HPC environments, which will make up a larger fraction of LHC computing resources in the future. Efforts should be made in the coming years to ease the adoption of ARC for other sites and to address scalability challenges of future workloads.

The time has come for a major rewrite of the AliEn middleware that manages grid operations for the ALICE experiment. A group at the Western Norway University of Applied Sciences participates in the jAliEn project (a Java rewrite of AliEn).

11 Education and outreach plans

Over the past few years we made a lot of efforts by providing data from the LHC experiments to the public, launching the CERN Open Data Portal in 2014. We will continue this work in the following years making use of substantial LHC Run 2 samples. Not only would it be important to make public more and more of the data acquired by the experiments, but also to provide tools and ideas on how to take advantages of the available data. Starting from the International Master Classes, which every year welcome thousands of high school students all around the world to analyze LHC data, one has seen the need for developing additional educational material (ZPATH) and analysis tools to be used at high schools outside of the Master Classes. We initiated developments of research projects adapted to university students, as a support to current courses. Brand new courses focusing on measurements and discoveries at LHC and other research infrastructures will follow. These projects and courses serve as good opportunities to convey advanced physics concepts and phenomena and introduce new ideas beyond today's theoretical framework describing the content of the Universe and its evolution. We intend to join the Extreme Energy Event network. We participated in the PolarQuEEEst mission with the goal to detect and measure cosmic rays at various latitudes simultaneously. We will continue with the involvement of Norwegian high-school and university students in building cosmic-ray detectors at CERN, operating them in Norway and taking data to be analyzed by students as part of school projects.

12 Conclusion

Norway has a vigorous and diverse program in particle and nuclear physics that will continue in the next European Strategy Update period.. The support and personnel involved in the ATLAS and ALICE experiments are expected to be maintained. Related to instrumentation, the ALICE community in Norway will contribute to the phase I upgrade, while the ATLAS community after completing R&D on 3D detectors will contribute to the tracker for the phase II upgrade. Although the Norwegian computing resources are sufficient to cover the next five years, a clear strategy will be worked out on how to reach a long-term sustained computing infrastructure towards HL-LHC.

Physicists from Norway who joined CTA plan to contribute to both the construction of the experiment and DM searches. In nuclear physics the activities in ISOLDE will continue.

The Norwegian high-energy theory community is growing and interconnecting via the N-PACT network. Spanning particle physics, astroparticle physics and cosmology, Norwegian theorists contribute to combining experimental discoveries on hot and dense QCD, electroweak scale phenomena, DM and gravitational waves with the aim to understand the fundamental properties of matter as well as the earliest history of the Universe.

Precision measurements of the Higgs boson and other Standard Model particles provide a promising gateway for new physics searches. Norwegian researches will continue to play important roles in studies of future machines at CERN, with a focus on linear collider related accelerator developments as for example CLIC. The accelerator physics program is well connected to studies of novel accelerator technologies. There is interest, on the physics, accelerator and instrumentation side, in smaller projects for light DM searches.

If the Japanese government gives green light for the construction of the ILC, physicists from Norway will participate in the accelerator and experiment, as it opens a new avenue for detailed SM studies on a timescale that is very interesting. In this context we rely on CERN to take responsibility to coordinate the European groups and create a platform in which also small countries like Norway can participate.