Canadian Submission to the European Particle Physics Strategy Update

Submission Theme: National Road Maps

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This document provides input from the Canadian subatomic physics community to the European Particle Physics Strategy 2020-2025 and is based on the 2017-21 Canadian Subatomic Physics Long Range Plan (www.subatomicphysics.ca). Major projects discussed in this document are submitting input to the European Particle Physics Strategy Update separately under the other submission themes/tracks where details of their specific efforts can be found. This submission provides an overview of the major projects in which the Canadian community is participating, and discusses connections to the European Particle Physics Strategy and prospects for further collaboration.

1 Overview of the Canadian Subatomic Physics Community

Subatomic physics research is a quest to discover and understand the basic laws that govern the universe. It spans an enormous range of phenomena, from the structure of atomic nuclei, to the composition of nucleons, to the elementary particles of the Standard Model (SM) and beyond. Remarkable progress has been made over the past 100 years of research to understand the fundamental constituents of nature, but a complete theory remains an elusive and exciting goal. Future advances will require international collaboration on both large and small projects.

The Canadian subatomic physics community is based at university departments and laboratories across the country and is coordinated through community planning. This planning is centred around the Institute of Particle Physics (IPP) and the Canadian Institute of Nuclear Physics (CINP) together with a group major scientific infrastructures and institutions:

- TRIUMF is Canada's particle accelerator centre, founded in 1968. TRIUMF, located in Vancouver, supports a spectrum of activities including a rare isotope beam facility, a facility for ultra-cold neutrons, detector and accelerator development, large-scale computing, as well as significant involvement in many off-site projects at CERN and beyond.
- SNOLAB has a campus 2 km underground near Sudbury, Ontario. SNOLAB hosts a number of experiments dedicated to understanding the nature of dark matter and neutrinos. The active collaborations working on SNOLAB experiments include researchers from over 17 countries including important contributions from Europe. SNOLAB also coordinates and collaborates with European underground laboratories in the UK, Spain, France, and Italy.
- The Perimeter Institute for Theoretical Physics is an independent, resident-based research institute in Waterloo, Ontario, devoted to foundational issues in theoretical physics.

- The Arthur B. McDonald Canadian Astroparticle Physics Research Institute, centred in Kingston, Ontario, coordinates the resources deployed for the astroparticle physics community. The McDonald Institute supports national and international programming and with eight partner universities and five partner institutions, has just launched a community driven process that will define a long term national strategy for an international program of astroparticle physics in Canada.

The overarching goal of the Canadian subatomic physics community is to address the major puzzles in subatomic physics. The 2017-21 Canadian subatomic physics long range plan identifies seven "Big Questions", which are listed below with the resources Canadian researchers are using, or plan on using, to address them.

- What is the nature of physics at the electroweak scale and beyond? Studies of the Higgs boson and searches for new physics at the energy frontier through ATLAS and its future high-luminosity and high-energy upgrades, as well as in future colliders and advances in accelerator physics. It also includes precision tests of the SM and fundamental symmetries below the electroweak scale with ALPHA, TUCAN, Belle II, NA62, MOLLER, and in rare isotope decays.
- What are the fundamental properties of the neutrino? Measurements of neutrino masses, mixings, and CP violation through T2K, Hyper-Kamiokande, DUNE, HALO, nEXO, SNO+, and IceCube.
- What structures underlie the forces and matter in the universe? Theoretical work in lattice field theory, quantum gravity, and other innovative approaches.
- What is the nature of dark matter in the universe? Searches for dark matter through direct detection in DEAP, DarkSide, NEWS-G, SuperCDMS, and PICO, at colliders with ATLAS and Belle II, and in cosmic rays with VERITAS and IceCube.
- How do quarks and gluons give rise to the hadronic properties and the phases of hadronic matter? Probes of nucleons with electroweak probes at JLab and MAMI, heavy-ion collisions at the LHC and elsewhere.
- How does the structure of nuclei emerge from nuclear forces? Probes of exotic nuclear structure and collective behavior with rare isotope beams at TRIUMF.
- How are the elements formed in the universe? Studies of nucleosynthesis reactions of relevance to astrophysics at the TRIUMF ISAC facilties, and abroad.

Efforts of the Canadian community on the projects of greatest relevance to the European particle physics strategy and their connections to it will be discussed in more detail below.

2 Extending the Energy Frontier

The discovery of the Higgs boson confirmed a central prediction of the SM but also gave rise to new puzzles. Much more work is needed to test the Higgs sector to the same precision as the rest of the theory and to look for potential new decay channels. The quadratic sensitivity of the SM Higgs mass parameter under quantum corrections also provides strong motivation for new physics in the vicinity of the electroweak scale that could be discovered at the LHC and planned future colliders. Canada's particle physics community is working to resolve these puzzles at the energy frontier through its involvement in ATLAS, its theoretical studies, and its work on upgrades and the development of cutting-edge detector technology.

Canada plays a significant role in ATLAS, one of the two large general purpose experiments at the CERN LHC. For the original ATLAS detector, two of the four liquid argon hadronic end-cap calorimeter wheels were designed and built at TRIUMF. The hadronic modules of the liquid argon forward calorimeters and the cryogenic feedthroughs for the liquid argon calorimeters were designed and built in Canada. The ATLAS physics goals include probing the mechanism for electroweak symmetry breaking and searching for new physics at the TeV scale. ATLAS consists of approximately 3000 physicists (including 1000 students) from more than 177 universities and laboratories in 38 countries. The multi-institutional ATLAS-Canada team, founded in 1992 and now consisting of approximately 130 faculty members, postdoctoral fellows, and graduate students, had central roles in the discovery of the Higgs boson in 2012 and first exploration of its properties. Canadian leadership in ATLAS is well recognized in overall management roles such as the upcoming as well as a previous deputy spokesperson of ATLAS and, in the past, publications committee chair, ATLAS collaboration board chair, and several other physics-group coordination roles. The ATLAS-Canada team is also playing a critical role in the instrumental upgrades of the experiment needed for the future running periods of the LHC. This includes construction of new muon detector elements and electronics upgrades for the liquid argon calorimeter for LHC Run 3, starting in 2021. At the High Luminosity LHC (HL-LHC), the average number of interactions per bunch crossing is expected to be about 200. Canada is contributing to the upgrades of the front-end readout electronics of the liquid argon calorimeter and the replacement of the inner detector with a completely new all-silicon detector. The new system will combine pixels and microstrips. Canada also provides one of ten international Tier-1 data intensive computing centres, operated by TRIUMF and now located at Simon Fraser University, for the ATLAS detector's distributed computing network.

Canada has made significant in-kind contributions to the LHC accelerator complex through TRIUMF, which includes contributions to the LHC injection kickers, twin-aperture quadrupole magnets, and upgrades to the injector synchrotrons. For the HL-LHC run starting in 2026, crab cavities will rotate bunches of subatomic particles before they collide, significantly increasing the luminosity of the collisions. Canada is a world-leader in the cryomodule technology and has committed to building five new crab cavity cryogenic modules containing the cavities. This project will leverage both TRIUMF's unique network of expertise and the capacity of Canadian industry to design, fabricate, and deliver the crucial upgrade components over five years. With a history of providing mission-critical cavity technology to international science collaborations and successfully transferring these technologies to industry, the Canadian community is well positioned to provide a high-impact, lasting contribution for the benefit of international science and society.

Canada strongly supports the LHC program, including the HL-LHC run, which offers unprecedented opportunities for testing the limits of the SM. The results from the LHC will have an immediate impact on the longer-term plans. Any discovery of physics beyond the SM could dramatically change the path forward. The proposed High-Energy LHC (HE-LHC) would approximately double the centre-of-mass energy with the use of novel higher field dipole magnets. This program would provide a valuable path towards understanding physics at the multi-TeV scale.

There are various other proposals for future colliders. A Global Design Effort completed a detailed ILC design report and published it in June 2013. Initially operating at a centre-of-mass energy of 250 GeV, the ILC will have the potential to increase this in the future. The high energy physics community awaits a decision on the ILC from the Japanese government. Studies for an alternative project at CERN, the Compact Linear Collider (CLIC) are also underway, which would operate at higher energies, up to 3 TeV, in a machine of length similar to the ILC. The higher collision energy will lead to significant improvements in the measurements of the Higgs boson self-coupling, and its couplings to SM particles. More recently, proposals for a 100 km collider at CERN (FCC-ee/hh) and in China (CEPC/SPPC) have drawn significant attention in the international community. Both projects envision initial operations as an electron-positron collider, which has as its main goal the precision study of Higgs boson properties. This would be followed by a hadron-hadron collider phase with a collision energy of around 100 TeV, which has the potential to uncover new physics at the energy frontier. Historically, Canada has been contributing to several CERN based particle physics experiments and research programs.

Particle theorists in Canada are very active in developing new techniques for the LHC experiments to test the properties of the Higgs boson. Theorists also explore physics beyond the SM such as supersymmetry, extra dimensions, and composite Higgs models, and propose ways to search for potential new phenomena at the LHC and future colliders.

3 Studies of Neutrino Properties

Neutrinos are seen to oscillate from one flavour to another. For this to occur, neutrinos must have masses and mixings among different lepton flavours, and this requires new physics beyond the SM. Canada has a multi-prong strategy to unravel the yet unknown neutrino properties through tests of neutrinoless double beta decay in EXO, nEXO, and SNO+, by characterizing neutrino oscillations with unprecedented precision with accelerator neutrinos in Tokai-to-Kamionkande (T2K) and Hyper-Kamiokande (Hyper-K), and through neutrino astronomy with IceCube.

The EXO and nEXO collaborations are searching for neutrinoless double beta decay, whose discovery would indicate the violation of lepton number and help to identify the origin and nature of neutrino mass. Canadian researchers in EXO, based at the WIPP facility in New Mexico, have contributed calibration systems, radon control, process system design concepts, veto system mechanical construction, and materials testing through ultra-trace assays. They have been active in the data-taking and analysis process. Moreover, the first analysis co-ordinator, a current run coordinator, and the current chair of the collaboration board are Canadian researchers. The Canadian team is also leading both the development of barium tagging, which has the potential to provide an exceptionally clean and sensitive probe of the neutrinoless decay in the upcoming nEXO project proposed for SNOLAB, as well as the development of silicon photomultipliers with unique wavelength, cryogenic, and low-radioactivity requirements. nEXO is expected to achieve unprecedented sensitivity completely covering the inverted mass hierarchy (which is currently disfavoured) within five years thanks to its large mass (5000 kg) and versatile background rejection capabilities.

The Canadian-led SNO+ experiment at SNOLAB will also search for neutrinoless double-beta decay and in addition aims to study low energy neutrinos produced in the sun by the pep and CNO cycles. The Canadian groups within SNO+ have major responsibilities for detector components, such as calibration hardware, calibration sources, cover gas, hold-down rope-net, water systems, scintillator systems, and isotope purification and loading. SNO+ is complementary to EXO as the two experiments use different isotopes and different technologies.

Canada is a founding member of the T2K collaboration in Japan, which is at the forefront of the world neutrino oscillation program. The critical concept of using an off-axis neutrino beam was initially proposed by a Canadian scientist, and its implementation at T2K was likewise spearheaded by a Canadian. The group was responsible for the design and construction of an optical transition radiation beam monitor that plays a critical role in the neutrino beamline operation, as well as for the fine-grained scintillating detectors and time projection chambers that form the core of the T2K near detector. The Canadian group also provides Tier-1 storage for T2K data, at TRIUMF, and about half of the collaboration's computation resources. Canadian T2K members sit on the collaboration's executive board, and their other leadership positions include run coordinator, analysis coordinator, and publications committee chair.

Canada is poised to continue its leadership towards the realization of the next-generation neutrino program, Hyper-K, which will make precision neutrino oscillation measurements, have world leading sensitivity for nucleon decay searches and supernova neutrino detection, and the capability to search for dark matter and study solar neutrinos. The Canadian group will shift towards the design and construction of the Hyper-K experiment, focusing on maximizing the scientific impact by addressing critical systematic uncertainties that should be controlled to maximize the experimental sensitivity. The interim program includes hadron production measurements with the EMPHATIC experiment (2017-2021), and designing (2017-2021), prototyping (2019-2022), and building (2022-2025) the intermediate water Cherenkov detector (E61 J-PARC experiment) for Hyper-K. E61 prototyping includes a beam test potentially situated in a new CERN low-energy beamline. CERN is soliciting input from the general community on the needs for such a beamline. This program will address the critical systematic uncertainties for neutrino flux modeling, neutrino interaction modelling, and detector systematics for Hyper-K. The primary Canadian hardware contribution to the intermediate water Cherenkov detector, in collaboration with European institutes, will be the development and construction of high resolution multi-PMT photosensors, which are also being considered for the Hyper-K detector and may constitute a significant contribution to the Hyper-K detector by Canada. Canada plans continued participation in Super-K and T2K to ensure continuity of scientific output. Moreover, Canada is open to the interests of all members of the community, in particular, support for other (U.S.) long-baseline experiments and we anticipate some members of the community joining the DUNE effort.

The supernova neutrino detection capabilities of Super-K and Hyper-K are complemented by the HALO experiment at SNOLAB, which has monitored for supernova neutrino interactions in 76 tonnes of lead as part of the Supernova Early Warning System (SNEWS) with high live-time since 2012. A 1000 tonne successor at Gran Sasso lab, HALO-1kT is planned using lead from the decommissioned OPERA detector. Canada has leadership in the HALO and HALO-1kT effort with a focus on mechanical design and low-background neutron detectors, and a HALO-1kT funding application is planned in 2019.

The Canadian IceCube program near the South Pole, which began in 2010, has established specific expertise in the study of neutrinos at energies up to the PeV scale and has played a central role in many aspects of scientific analyses within the international collaboration. The Canadian groups provided the computing resources that led to the discovery of a diffuse high energy astrophysical neutrino flux, appearing as the cover story of Science, November 2013. The Canadian IceCube groups are involved significantly in the study of low-energy neutrinos in order to enhance sensitivity to the neutrino properties, as well as the development of the IceCube Upgrade.

An area of significant overlap between nuclear and particle physics is that of neutrino-nucleus/ nucleon scattering measurements and the theory needed to reduce the sizable neutrino-scattering uncertainties in long baseline neutrino measurements. This is a very important issue that dominates the systematic uncertainties in neutrino-nucleon/nucleus cross sections, ultimately limiting the precision of the extracted neutrino oscillation parameters from these measurements. We encourage further investments in this field, particularly for dedicated studies such as performed by the T2K-ND280 neutrino-nucleus program and the MINERνA Collaboration at FermiLab, and supporting phenomenology.

4 Fundamental Symmetries at the Precision Frontier

Experiments that measure SM symmetries below the electroweak scale can achieve exquisite precision and are potentially sensitive to new physics at energies well above the electroweak scale. Such experiments often have the greatest reach when they probe the exact and approximate fundamental symmetries of the SM, such as P, CP, CPT, and flavour. In particular, the discovery of new sources of CP violation could shed light on how the asymmetry of matter over antimatter was created in the early universe. Lower energy experiments can also yield excellent tests of dark sectors consisting of new particles and forces that interact only very feebly with the SM. The Canadian subatomic community is pursuing these directions through its involvement in ALPHA, TUCAN, Belle II, NA62, MOLLER, and rare isotope measurements at TRIUMF.

ALPHA is an international experiment at CERN that aims to study CPT invariance with anti-hydrogen spectroscopy and to test for possible differences between the gravitational interactions of matter and antimatter. ALPHA-Canada has played a signficant leadership role in the project and members of the team have made critical contributions to the instrumentation of ALPHA, the successful demonstration of anti-hydrogen trapping and subsequent trapping for 1000 seconds, and measurements of anti-hydrogen spectroscopy. Recently, the collaboration performed a 1S-2S laser spectroscopy measurement at a precision of 2×10^{-12}, the highest ever achieved in any antimatter experiment. Also, they succeeded in detecting the Lyman-alpha (1S-2P) transition, which will enable laser cooling of antihydrogen atoms. The new focus on measuring the gravitational interaction between antimatter and the earth, called ALPHA-g, receives most of its financial support and much of its scientific leadership from Canada. The Antiproton Decelerator (AD) facility at CERN provides the world's unique capability to deliver low energy antiproton beams. ELENA is an upgrade project to the AD under construction, which received contributions to the conceptual design of its electrostatic beam lines from TRIUMF. The combination of AD and ELENA will significantly increase the intensity of antiproton beams and their availability to the experiments like ALPHA.

The TUCAN (TRIUMF Ultracold Advanced Neutron) experiment aims to measure the neutron electric dipole moment (nEDM) to the level of $10^{-27}\,\mathrm{e\,cm}$, more precisely than ever before. A new measurement of the nEDM would place even tighter constraints on new sources of CP violation beyond the SM. Such sources are expected because they are a necessary ingredient to explanations of the predominance of matter over antimatter (baryon asymmetry) in the universe today. The key tool in this search is the new source of ultracold neutrons (UCN) at TRIUMF. UCN are slow moving neutrons that can be stored in material, magnetic, and gravitational bottles. Once they have been confined using such methods their properties can be studied very carefully, as required for precision nEDM tests. It should be noted that TUCAN is one of several nEDM efforts worldwide. Due to the very challenging nature of the experiments, multiple approaches and cross-checks are vital. Close ties have been forged with the UCN/EDM projects at Technische Universitaet Muenchen, Paul Scherrer Institut, Villigen, Switzerland and Institut Laue-Langevin, Grenoble, and new collaborators from Europe on TUCAN are invited. The future important facility for this field could be the European Spallation Source in Sweden, and it is important to support a strong fundamental physics program there, based on both cold and ultracold neutrons.

Belle II at KEK in Japan is the Υ ($b\bar{b}$) meson facility that has recently begun taking data. The experiment, which depends on substantial contributions from Europe, will test the flavour structure of the SM in greater detail than ever before. The enormous luminosity of the experiment also makes it an ideal tool to search for new particles and forces that couple only very feebly to regular matter, such as dark photons and possibly even dark matter. The Canadian team is responsible for calorimeter calibration, pulse shape discrimination in CsI(Tl), and other reconstruction software, GEANT simulation, and beam background monitoring and mitigation. Thanks to the development in Canada of cloud computing for Belle II, Canada is contributing significantly to the computing needs of the experiment and will help lead analysis efforts on the data to collected in the years to come. Canadians have also spearheaded the effort, with accelerator physicist colleagues from the U.S. and Japan, to examine the feasibility of introducing polarized electron beams into SuperKEKB as an upgrade of the facility to be completed in the mid-2020's. If implemented, this will yield unprecedentedly precise electroweak couplings of b, c, s-quarks, as well as all three charged leptons and provide other unique probes of new physics at the TeV scale. Contributions to this accelerator upgrade effort from Europe will likely be requested.

The NA62 experiment at CERN is studying charged kaons decaying in flight to charged pions and neutrinos. Measuring the rate of this rare decay would test the flavour structure of the SM, and significant deviations could provide evidence for new sources of flavour mixing well above the electroweak scale. This experiment is also sensitive to exotic rare kaon decays to dark matter and can be run in a beam dump mode to search for dark photons. The Canadian group is playing an important role in the analysis of the NA62 data by bringing unique expertise acquired in previous experiments at TRIUMF and Brookhaven National Laboratory (BNL).

The MOLLER experiment at JLab in the United States will measure the electron's weak charge and weak mixing angle through parity-violating electron-electron scattering. These measurements will probe the electroweak structure of the SM and will be sensitive to new physics at the TeV scale, accessing new discovery space. The Canadian group led the recent publication of the ground-breaking Compton polarimeter results. Canadians are also DOE level 2 managers for the spectrometer development and package leaders for the integrating detector package. MOLLER builds on the recent success of the Qweak experiment at JLab, where Canadians played a major role. Qweak's final result (Nature, 2018) is the best measurement of the weak mixing angle at low momentum transfer to date and the first precision measurement of the proton's weak charge. There is also a well established collaboration between the Canadian, U.S., and German parity violating electron scattering communities, both on MOLLER and the P2 experiment, the latter being under preparation at the MESA facility in Mainz, Germany.

Rare isotopes provide a powerful tool for testing the flavour and electroweak structure of the SM, and the ISAC rare isotope beam facility at TRIUMF hosts a diverse range of experiments in this line. The GPS, GRIFFIN, and TITAN experiments at TRIUMF have recently produced high-precision measurements of several superallowed beta decays that further constrain weak scalar currents and provide a new benchmark for testing isospin symmetry breaking in nuclei. Several Canadian research groups have also made important contributions to the determination of weak currents and the most precise value of the SM quark-mixing parameter V_{ud}. The TRINAT neutral atom trap has been setting best limits on weak interactions for more than a decade and is considered to be the world's leading beta decay correlation experiment. The Canadian-led FRPNC collaboration has established a francium trapping facility at ISAC to measure atomic parity violation, an effect that is enhanced in francium (18 times relative to cesium) and which is sensitive to new physics, such as extra gauge bosons or leptoquarks. A laser-cooled atomic fountain for cesium is also being prepared at Lawrence Berkeley National Lab to search for the electron's time-reversal-violating electric dipole moment, with a letter of intent to bring it to TRIUMF. These research programs will be enabled further by the ARIEL expansion of TRIUMF with the capability to deliver multiple beams simultaneously. This is complemented by studies offshore, such as at the Canadian Penning Trap at Argonne (ANL, USA), which is studying β-neutrino correlations in ^{8}Li and ^{8}Be.

5 Searches for Dark Matter

Dark matter makes up the vast majority of the matter in the universe but its nature remains a mystery. Canada is involved in several direct dark matter search experiments, including DEAP, which is optimized for weakly interacting massive particles (WIMPs) with masses above about 10 GeV; PICO, which is optimized for spin-dependent interactions and SuperCDMS and NEWS-G, both of which are optimized for light dark matter particles. In addition, Canadian researchers play central roles in VERITAS, which searches for dark matter annihilation within and beyond the Milky Way, and in collider searches for dark matter at ATLAS and Belle II.

The DEAP-3600 detector based at SNOLAB uses nearly 3.3 tonnes of liquid argon to search for WIMPS and is primarily sensitive to spin-independent WIMP scattering with masses above about 10 GeV. The DEAP collaboration is led by Canadian researchers and includes members from the UK and Mexico, and the detector has been operating at SNOLAB since 2016. Scientists at Canadian institutions chair the groups responsible for low-level signal processing; calibration; pulse shape discrimination; event reconstruction; the backgrounds; run selection, data-quality and live-time; data-flow and software management. The major argon collaborations in North America and Europe of DEAP, Darkside, ArDM, and MiniCLEAN have created the Global Argon Dark Matter Collaboration with the near term goal of a 20 tonne detector at the Laboratori Nazionali del Gran Sasso, and a long-term goal of a $\sim$300 tonne liquid argon detector sensitive to the coherent neutrino-nucleus scattering signal from atmospheric neutrinos.

The PICO experiment at SNOLAB uses a bubble-chamber technique to look primarily for spin-dependent scattering of dark matter on target nuclei. The PICO collaboration spans six countries, including the Czech Republic and Spain, and Canadians represent more than 40% of the total membership. The modest scale of the PICO experiment, which is located at SNOLAB, allows Canadian students and postdocs to be heavily engaged in all aspects of the experiment, including design, construction, commissioning, operation, and analysis.

NEWS-G is optimized to search for light dark matter particles below 10 GeV using spherical gas TPCs with a variety of potential light noble gas target materials. NEWS-G is a Canadian-led experiment with strong European contributions to be located at SNOLAB, but benefiting strongly from an excellent connection with the Modane underground laboratory.

SuperCDMS also searches for light dark matter particles ($\lesssim$ 10 GeV), but with a different approach using cryogenic Ge and Si detectors with very low energy thresholds. Canada makes major contributions to the experimental infrastructure, presently being installed at SNOLAB, and is leading the development of the DAQ system. The experimental setup is designed with an upgrade in mind that will be able to reach the ultimate sensitivity, which is limited by the coherent interaction of solar neutrinos. This will require a considerably larger payload and improved detector technology. Discussions are underway with the European cryogenic dark matter experiments CRESST and EDELWEISS regarding a potential cooperation in reaching this goal.

Unique opportunities for detector testing and characterization will open in 2019 thanks to the construction of a well shielded detector test facility (CUTE) at SNOLAB, which is fully funded by Canadian SuperCDMS groups. This facility is also available to test detectors and other cryogenic components for a future upgrade that may be provided by European partners.

Canada continues to play a central role in VERITAS, a ground-based gamma-ray instrument operating at the Whipple Observatory in Arizona, USA. In addition to helping lead physics analyses, the Canadian group supplied components to build the telescopes and has developed a number of devices to provide precise calibrations.

Complementary to the direct and indirect searches, colliders might be able to create dark matter in the laboratory and test its interactions with visible matter. Relative to direct detection experiments, they have greatest sensitivity at lower masses (below about 10 GeV) but also provide useful information for larger masses. ATLAS searches cover a broad range of potential masses and can also probe how the dark matter connects to regular matter. Lighter dark matter can also be produced at Belle II, and a dedicated program of searches for dark matter and new dark forces is underway.

Canadian particle theorists also study dark matter, both in terms of building dark matter models and predicting signals that dark matter could leave in different kinds of experiments. In various models, the dark matter is part of a sector containing very light states (the dark matter itself and/or some mediator) that couple very weakly to the SM. Generically, such very light particles would be difficult to detect at colliders, so other experimental techniques might be better suited for this task. Theorists have been actively exploring how these new light states could be detected at neutrino experiments, meson factories, and beam-dump or fixed-target experiments.

6 Hadronic Physics and the Phase Diagram of QCD

The detailed understanding of the internal structure of hadrons in terms of QCD, is another area of overlap between nuclear and particle physics. The Canadian program is largely centreed on experiments at JLab, such as the search for exotic hybrid mesons at GlueX, studies of meson form factors in Hall C, and studies of nucleon structure at lower energy at MAMI (Mainz, Germany). It also includes an active QCD theory effort including AdS/QCD, Lattice QCD, and perturbative QCD.

Longer term, interest is building for Canadian participation in the Electron-Ion Collider (EIC), a major initiative to construct a high luminosity facility in the U.S. to collide beams of spin-polarized electrons with beams of both polarized nucleons and unpolarized nuclei from deterium to uranium. The central scientific issues to be addressed by an EIC are: 1) the mechanism by which the mass of nucleons, and hence of all the visible matter in the universe, is generated; 2) the origin of nucleon spin; 3) the role of gluonic interactions in nucleons and nuclei. The EIC was recently reviewed by the U.S. National Academies of Sciences, Engineering, and Medicine, who found the scientific case for the facility to be "compelling", and the Canadian long range plan speaks favourably of the EIC as a possible opportunity for future international collaboration. We encourage an expansion of this international collaboration, including investments in detectors, accelerators, and the new generation of physicists needed to take best advantage of this facility.

Another major international facility currently under construction is the Facility for Antiproton and Ion Research (FAIR) at Darmstadt, Germany. The program of this facility is very broad. We see FAIR as an important facility for international collaboration, providing access to a wide variety of neutron-rich nuclei, and complementing the hadron structure studies at JLab (and ultimately the EIC).

At the highest densities, yet at still rather low temperatures, the quarks making up the nucleons of nuclear matter may form a new state of matter which is colour-superconducting. Exotic nuclear matter can also be created by colliding nuclei at relativistic energies. In this case, 'nuclear temperatures' can reach values that represent a state of matter (the quark-gluon plasma) as it existed during the first moments after the Big Bang. This is of course an integral part of the LHC program at CERN, and an important area of fruitful collaboration between nuclear and high energy physics.

Canadian theorists are contributing to the understanding of the phase diagram of nuclear matter, providing insight into the exotic nuclear matter that existed during the first moments after the Big Bang. One of the achievements of the relativistic heavy-ion program at RHIC, which was confirmed at the LHC with ATLAS-Canada participation, is the success of relativistic fluid dynamics, as championed by theorists from Canada.

7 Scientific Infrastructure and Computing

TRIUMF operates a state-of-the-art accelerator complex featuring the world's largest cyclotron and most powerful superconducting electron linear accelerator. The 500 MeV proton cyclotron is used as a driver to create beams of protons, muons, and rare isotopes, and is the source for the TRIUMF ultra-cold neutron facility. The ARIEL upgrade at TRIUMF will provide a new high-intensity electron beamline and allow for the simultaneous extraction of multiple beams from the main cyclotron. Accelerator physicists at TRIUMF working with Canadian partners have provided important support to many international accelerator projects and will contribute to the HL-LHC upgrade. TRIUMF also fosters science and technology by providing technical resources for the design, construction, and commissioning of experimental detectors and other apparatus.

The SNOLAB underground laboratory has 5,000 m^2 of clean space at a depth of 2000m, providing a low-background environment for the staging of many experiments. In order to facilitate clean detector development, the full 3,100 m^2 of experimental laboratory space is a class 2000 clean room. There is an additional 2,600 m^2 of excavation outside this space used by SNOLAB for the service infrastructure and material transportation and storage. The SNOLAB campus also includes a surface building with detector assembly facilities, clean space, and machining capabilities.

Detector development and construction infrastructure is also provided to the entire Canadian community by technology support groups located at University of Montreal, Carleton University, the Universities of Alberta and Victoria. The McDonald Institute based at Queen's University provides detector development and construction infrastructure support focused on the SNOLAB program.

In recent years, the computational demands and the amount of data in particle physics has increased exponentially. TRIUMF operates one of ten international Tier-1 data intensive computing centres for the ATLAS detector's distributed computing network, part of the globe's largest and most advanced scientific computing grid. With rapid advances in large-scale computing, big data, machine learning, and quantum computing, these technologies are beginning to have serious implications for fundamental research. Germany's Helmholtz Association and TRIUMF together with local industry partners have signed a Memorandum of Understanding to jointly establish corresponding Canadian and German quantum computing and machine learning networks and to collaborate on initiatives of mutual interest.

The Perimeter Institute supports theoretical physics in Canada and beyond. Specific initiatives include direct research, joint faculty appointments with universities, hosting visiting researchers, the TRISEP summer school in particle physics together with SNOLAB and TRIUMF, hosting of conferences and workshops, and an affiliate visitor program for Canadian faculty.

8 Summary

Canada has significant involvement in a number of world-leading facilities and experiments at the frontiers of subatomic physics. In addition, research in theoretical subatomic physics suggests new paths for discovery and provides the foundation for interpreting experimental results. To ensure Canada's continued success in subatomic physics, the Canadian Subatomic Physics Long Range Plan Committee has developed recommendations for the 2017-2021 period in consultation with the broader community. The recommendations flow from the following key principles, which have brought the field in Canada to where it is today:

- participate at the highest possible levels, assume leadership roles, and tackle the most important research problems;
- ensure high impact by concentrating effort and taking on major responsibilities in world-leading subatomic physics projects;
- strategically participate in innovative smaller-scale projects with the potential of significant discovery;
- maintain capacity and flexibility to take advantage of new scientific opportunities as they arise;
- fully engage undergraduate, graduate, and postdoctoral students in all aspects of scientific research; and
- deliver on promises to Canada and international research partners.

There is much opportunity for fruitful collaboration between the Canadian and European subatomic physics communities. Current collaborations have been outlined in this document and we look forward to a continuation of this with the HL-LHC, the Global Argon Dark Matter Collaboration, Hyper-Kamiokande. The Canadian community also looks forward to helping to develop and then support the global consensus on potential new long-range large projects under consideration, including the EIC, ILC, CLIC, HE-LHC, FCC, CEPC and others.

Another example of fruitful collaboration is the placement of observer members on each other's high level science committees. We note that the Canadian Subatomic Long Range Plan Committee included Europeans and the Physics Preparatory Group includes a Canadian. We believe there is great benefit to both Canada and Europe in having individuals from our respective communities participating in each other's planning processes and encourage this practice to continue into the future.