INSTITUTE OF PARTICLE PHYSICS

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Institute of Particle Physics 2022-2026 Long Range Plan

IPP Scientific Council[1]

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DRAFT for IPP Member Feedback

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Executive Summary

The members of the Institute of Particle Physics (IPP), through which Canadian particle physicists are self-organized, are addressing the most important and pressing fundamental scientific questions today. Through the IPP, Canada is having a disproportionately high impact on international particle physics projects and the goal of IPP during the period 2022-2026 is to maintain that leadership in the field. This brief documents how IPP plans to do that.

- **Big questions in Particle Physics**
  The overarching goal of the IPP community is to continue to make significant progress on answering the "Big Questions" of our time:
  - Is there new physics at or above the TeV scale accessible to the LHC direct searches and precision measurements or rare decays from multiple experiments?
  - What is the nature of the dark matter (DM) that comprises 85% of matter in the universe?
  - Is there a hidden "dark sector" ?
  - What is the origin and nature of the matter-antimatter asymmetry that produced our matter-dominated universe?
  - What is the nature of the neutrino and what can we learn by probing neutrino oscillations?
  - How are gravity and dark energy incorporated into the rest of the particle physics theoretical framework, and how can that knowledge be used to understand the history of the universe?

  In tackling these questions IPP members train the next generation of scientists in multiple, high-level skills at the cutting edge of science, technology and problem solving in a competitive international environment. IPP members focus their efforts on those projects most likely to generate answers to the above questions using facilities both in Canada and around the world. For many of these experiments, substantial upgrades to improve the sensitivity and likelihood of discovery are planned for operations beyond 2026. Most require funding decisions in 2022-2026 including the successful development of advanced technologies.

- **Support for Experiments**
  Among the set of projects that will take data during the period of the Long Range Plan a subset was identified as "essential" to the Canadian particle physics community based on the level of engagement of the researchers in the projects, scientific and technological training of the next generation, Canadian investments in those projects to date, and on their potential scientific payoff. These essential projects are:
  - ATLAS, directly probing the energy frontier;
  - Belle II and TUCAN, two precision frontier experiments which are sensitive to new physics;
  - DEAP, PICO-500 and SuperCDMS which are complementary direct dark matter detection projects;
  - SNO+, the search for neutrinoless double-beta decay;
  - T2K and IceCube, complementary programs probing neutrino mixing.

  Three of these essential projects are transitioning programs, with the new phases also at the highest priority but not necessarily taking data during the Long Range Plan period. These transitioning programs are: ATLAS at the upgraded High Luminosity LHC; DEAP at SNOLAB with the Canadian team moving to DarkSide-20k at LNGS; and T2K with the group largely moving to Hyper-K.

  There are also a number of important projects that will not be taking data during this period, including DUNE and MOLLER, as well as Chiral Belle, MATHUSLA, and nEXO. Some of these experiments will become essential as they approach data-taking operation depending on the level of Canadian effort and breadth of the physics program, while the latter group also require final approval.

  Other projects that will be taking data during the LRP period with focussed discovery potential include MoEDAL, NA62, P-ONE, HALO/HALO-1kT, NEWS-G, the Scintillating Bubble Chamber (SBC) and LEGEND-1000 (if approved). VERITAS is in the final data analysis phase of the project. It is important to ensure that some resources are allocated to smaller projects, especially those in the early stages of development.

  In the longer term, there is also wide interest from Canadians in a possible International Linear Collider (ILC), a new circular collider (FCC-ee) and a massive underground liquid argon dark matter detector, ARGO.

  The detailed project prioritisation is discussed in Section 9 of this brief.

- **Support for Theory**
  Particle physics theorists develop the understanding of these "Big Questions" and are crucial in helping to solve them. In order to ensure the vitality of the Canadian theory community, and indeed the entire community, it is essential that it continue to be assured that sufficient funding is allocated to theory Discovery Grants in particle physics. The funding is particularly needed for the Theory community to keep their contingent of students and postdocs approximately scaling with the level of effort of the experimental community.

- **Program Support**
  In order to fulfill these aspirations and fully leverage the capacity of particle physics faculty to train HQP and for our researchers to undertake new detector and accelerator related R&D, as well as to operate the experiments, increases to the NSERC Subatomic Physics envelope will be required. There will also be an increasing draw on funds from the Canadian Foundation for Innovation (CFI). IPP stresses that:

  - the IPP community has been growing, driven by hires of younger faculty members including about a dozen McDonald Institute members who will have completed a transition to being NSERC grant eligible by 2023. The Subatomic Physics envelope increase is also essential to support these new, dynamic researchers;
  - essential R&D in particle detector and accelerator technology requires modest and timely investments in equipment and expertise, funds for which are not available outside the SAP envelope. Support for the NSERC Research Tools and Instruments (RTI) and Major Resources Support (MRS) programs is critical to our field;
  - the on-going contributions of CFI via its Major Science Initiative (MSI) Fund to the operation of SNOLAB and Compute Canada facilities is essential for our community;
  - the New Digital Research Infrastructure Organization (NDRIO) is strongly encouraged to continue to work with members of the IPP community to ensure that the evolution of Canadian digital research infrastructure meets our needs;
  - continued support for CANARIE is absolutely essential for the success of the IPP program;
  - major contributions to particle physics experiments now depend on the CFI Innovation Fund program, and consequently its continuance is also essential for our community.

  The community also expects to continue to draw heavily on resources at TRIUMF, SNOLAB, IPP and at the universities for developing and executing the experiments in the future. It is of the utmost importance that the Government of Canada via ISED, NSERC, NRC, CFI and NDRIO coordinate their work in support of particle physics, along with IPP, TRIUMF, SNOLAB and the Perimeter Institute, to avoid making independent decisions on funding and resource allocation. Projects of this size require "cradle-to-grave" consideration by the funding bodies.

- **Institutional Support**
  Because the success of the field in Canada depends critically on TRIUMF, SNOLAB, Perimeter Institute and the IPP Research Scientist program, it is essential that these resources be supported and properly funded going forward. As CERN plays such a critical role in particle physics world-wide, it is important that the Long Range Plan also consider Canada's relationship with CERN and how it may develop in the future.

- **Increases to the NSERC Subatomic Physics Envelope**
  Increased funding to the envelope is critically needed in order to address the growing demands on the envelope for essential technical, maintenance and operations support, in addition to normal inflationary stresses. These demands are resulting in less funding for HQP training, and hence fewer students and postdocs being trained. With sufficient increased funding to the SAPES envelope, this community will not only address the HQP funding crisis, but be able to cover all the discovery bases. Through their work on SNO, ATLAS, and BaBar, Canadians have had a key role in the science associated with all three recent Nobel Prizes in Physics awarded in particle physics - the discovery of neutrino oscillations (2015), Higgs mechanism (2013), and CKM CP violation (2008). Sufficient increases to the envelope will ensure that Canadians continue to be key players in the scientific advances recognized by Nobel Prizes in particle physics in the foreseeable future.

A major discovery in particle physics during the 2022-2026 period is a real possibility and IPP members are positioned to be major players whether that occurs at the energy or precision frontier, in the direct detection of dark matter or other dark sector particles, or via the discovery of CP or lepton number violation in the neutrino sector.

Contents

1 Introduction

This document has been as input into the 2022-2026 Canadian Subatomic Long Range Planning (LRP) process. It describes the scientific goals and plans of the members of the community over this period and discusses the resources required and timelines associated with achieving those goals. Several calls for input to the IPP membership were made following the launch of this current Long Range Plan and the members enthusiastically responded. In conjunction with its 2020 Annual General Meeting in June, the IPP organized a three-day town-hall meeting in July of its members where presentations on particle physics efforts in Canada were made and a forum for discussion provided. The experimental projects presented at the town-hall ranged from efforts involving a few to several dozen grant-eligible members and projects at various stages, from those still at the R&D stage through to those approved and funded for data-taking during the 2022-2026 period. Written submissions were then solicited from the presenters and the teams they represented. These submissions and discussions were the input to this document.

With our colleagues around the world, the Canadian particle physics community is fully engaged in tackling the most pressing and important fundamental scientific questions of our time: What is the nature of the dark matter (DM) that comprises 85% of matter in the universe? What is the origin of the matter-antimatter asymmetry that produced our matter-dominated universe? How is gravity incorporated into the rest of the particle physics theoretical framework and does the large difference between the strengths of the electroweak interaction and gravity imply the existence of new physics at the TeV scale? What theories beyond the Standard Model (BSM) that might explain these puzzles are ruled out or validated at the experimentally available energy and precision frontiers of knowledge and is the Standard Model (SM) still valid at those frontiers? What is the nature of the neutrino? Are they Dirac or Majorana? Is the mass hierarchy normal or inverted? Is CP violated in the lepton sector?

The ability to access international, cutting-edge facilities is essential to our field. In the past the informal understanding of reciprocity of access has been the practice: our colleagues from Europe, Asia and the U.S. have access to TRIUMF and SNOLAB and in return Canadians have had access to labs in the U.S., Japan, and Europe. When major new accelerator projects arise, it is expected that Canada will provide some in-kind contribution to the accelerators. This was most recently done for the High Luminosity LHC upgrade. In this Long Range Plan period it is important to recognize that such a model, and the funding implications, is likely to continue; for example, if the International Linear Collider (ILC) is approved in Japan, Canadian expertise in super-conducting radio-frequency particle acceleration technology would be valuable to the success of the project. It is also possible that Canada will be asked to develop a closer relationship with CERN. Associate CERN membership, for example, has been discussed at various levels in the past and provides clear advantages to Canadian industry. The size of the SAP envelope however, precludes funding the dues of such an Association from that source and other sources would need to be identified within the government of Canada.

Through the IPP, the Canadian particle physics community historically has been very successful in prioritizing resource allocation for projects by determining:

- whether a project addresses some of the most important scientific questions of our time;
- how effectively the project addresses the question(s);
- how much impact the Canadian team has on the overall effort based on the excellence of research team and their contributions to the overall project;
- whether a project maintains the successful Canadian practice in particle physics of focusing our limited resources and effort on non-competing projects to ensure we have the highest impact on those projects with which we are already involved.

We fully expect that as resources are allocated these will continue to be the primary guiding principles. They have enabled this community to have a significant impact on the field as a whole and in every particle physics experiment where Canadians have been involved. For an experiment to be approved as an IPP Project all four criteria are expected to be met in addition to the criterion that the project is approved and funded by the host country. Substantial non-Canadian contributions to a project is one of the indicators of the strength of the scientific case for a project. As additional input into the assessment of the community's priorities, the scientific priorities of individuals within the community are documented here and the priorities of individual grant-eligible researchers as measured by the fraction of their research time allocated to particular projects is used as an indicator of the priorities of the community as a whole. Another vital consideration in establishing the priorities of resource allocation is the obvious requirement that investments in the design, construction and successful commissioning of an experiment be supported for its scientific exploitation phase.

This document is structured to initially present an overview of the landscape of particle physics in Canada. This is followed by a summary of the activities and plans of the particle physics theory community. It includes a discussion of the way the researchers work and interact with each other, their students, postdocs, and where appropriate, their experimental colleagues. This is followed by a section dedicated to IPP Projects that will be drawing on resources for the period from 2022 and beyond. Experiments that are not (yet) IPP Projects are then presented in the following section. In the descriptions of each of these activities we discuss which "Big Questions" are being addressed and the effectiveness of the approach to addressing those questions, the role of Canadians in the projects, how the project is related to other projects in the program, and the resources required. We also discuss how the projects have trained or will train graduate students and postdocs - highly qualified personnel (HQP). This field depends critically on the research, development and implementation of many cutting-edge technologies. We discuss the detectors, accelerators, data management and computing technologies that must be developed and the resources needed to execute the projects in the coming decade. The community's activities related to improving Equity, Diversity and Inclusion in particle physics are discussed in Section 7 and examples of the broader impact of the community's work on Canadian society are presented in Section 8.

2 The Canadian Particle Physics Landscape

Through its participation in various scientific projects, the Canadian particle physics community is engaged in addressing all of the most compelling scientific questions of our field. These questions are grouped in terms of general areas of scientific inquiry: inquiries related to dark matter and the dark sector, searches for new physical phenomena at energies beyond the TeV scale, investigations of the differences between matter and antimatter, and explorations of the nature of the neutrino. Neutrinos can also be used as a messenger from the cosmos to do astronomy, and several experiments have the ability to do so. Figure 1 presents the experiments that are discussed in this document and which of these broad areas of inquiries they address.

In addition to the experimental program, the Canadian particle physics community is very active in theoretical work aimed at addressing a wide array of fundamental questions in particle physics that includes those in Figure 1.

The DEAP, PICO and SuperCDMS IPP projects are designed to detect possible interactions of dark matter particles within their fiducial volume (the DEAP team is transitioning to the larger DarkSide-20k during this planning period). The complementarity of these projects lie in the experimental techniques used, which in turn result in each experiment having a different and complementary sensitivity to dark matter interactions. The IceCUBE, VERITAS and Hyper-K experiments, on the other hand, have the ability to search for different experimental signatures associated with the possible annihilation of dark matter particles within and beyond our galaxy. The ATLAS experiment carries out searches for evidence of the opposite process, i.e. creating dark matter or dark sector particles from the interaction of known particles. With the ability to carry out precision measurements and search for rare processes, the Belle II and ATLAS experiments will have the ability to search for dark matter particles and hypothetical particles associated to various dark sector models. Other experimental programs into the nature of the dark matter/dark sector identified as having Canadian participation, and which may in the future become IPP projects, include NEWS-G, MATHUSLA, MoEDAL and the ILD. In summary, on the time scale of the current long range planning exercise, the Canadian community will be engaged in a number of complementary approaches of addressing the existence and nature of dark matter and possible dark sector.

The IPP projects particularly sensitive to new physics at or above the TeV scale are ATLAS at the LHC energy frontier, Belle II at KEK, and NA62 at CERN. Belle II and NA62 are precision experiments designed to further challenge the SM and are complementary to the LHC with superior reach for some new physics scenarios. Searches for proton decay at Hyper-K and DUNE are sensitive to new physics many orders of magnitude above the TeV scale. Other potential new IPP projects, sensitive to new physics, discussed in this document include Chiral Belle, the Scintillating Bubble Chamber (SBC), TUCAN at TRIUMF, MOLLER at JLAB, and the International Large Detector (ILD) at the International Linear Collider (ILC) which would take place later.

The differences between matter and antimatter will be investigated by ATLAS, Belle II and T2K/Hyper-K. Both ATLAS and Belle II will provide insights into flavour asymmetry from the study of different processes, while T2K, Hyper-K and DUNE will study the matter-antimatter asymmetries in the neutrino sector. Potential new IPP projects contributing to this line of inquiries include TUCAN at TRIUMF and the ILC.

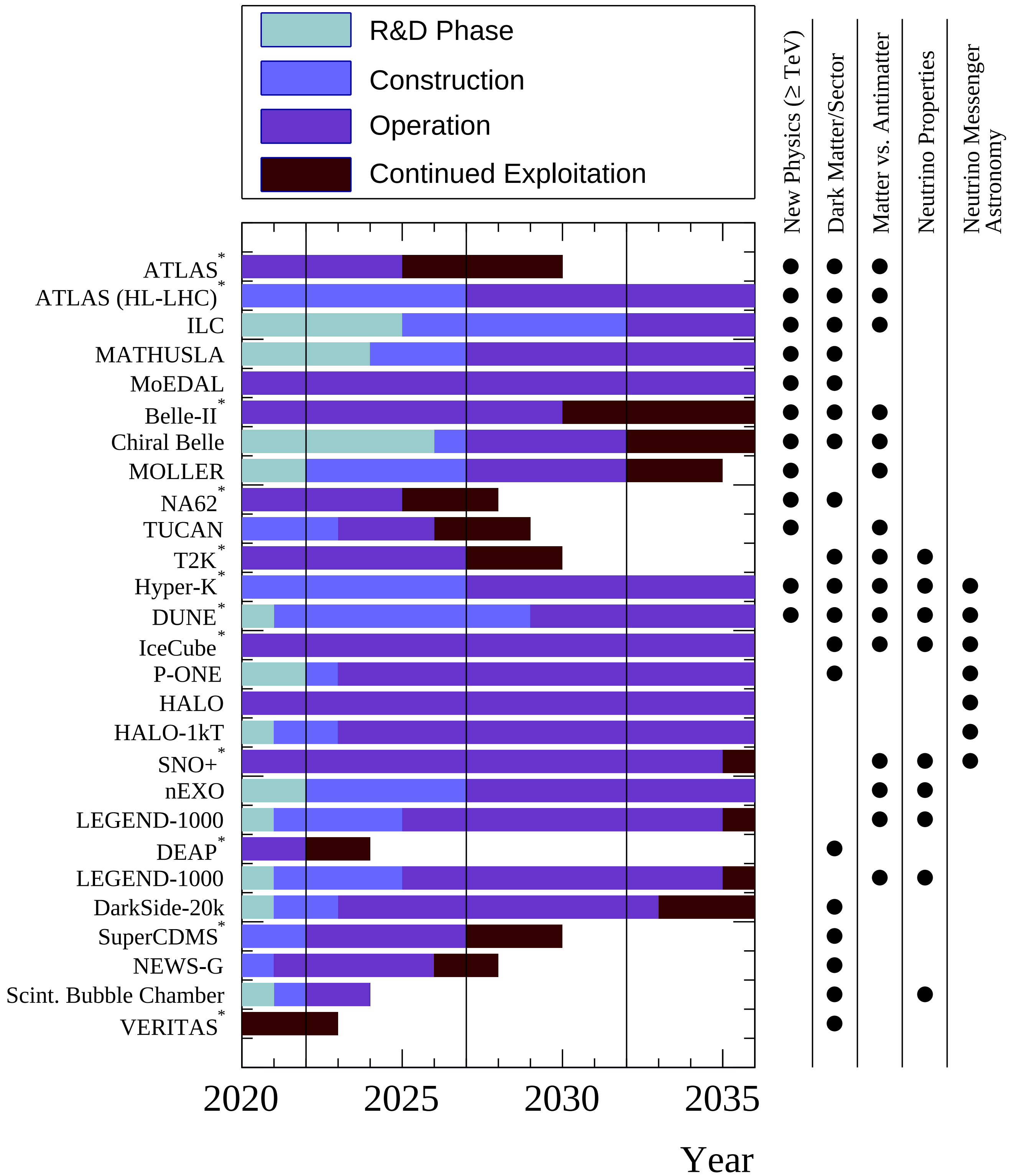

Figure 1: Projects discussed in this report, and the physics topics each addresses. The "*" indicates approved IPP projects. The filled circles on the right indicate the physics topics addressed by each experiment.

Investigations of the nature of the neutrino will be carried out by several different projects. The SNO+ IPP project and the nEXO and LEGEND-1000 experiments are designed to search for neutrinoless double-beta decay which would provide direct insights into the nature of the neutrino and could determine if the neutrino and anti-neutrino are in fact the same. In addition to relying on different experimental techniques and double-beta decaying isotopes, the projected sensitivity over time of these two experiments is complementary. In addition, the T2K, IceCube, Hyper-K and DUNE projects study the nature of neutrino mixing. Their investigations are done using widely different experimental techniques; T2K, Hyper-K and DUNE are accelerator-based experiments while IceCube and P-ONE are designed to study neutrinos from astrophysical sources.

Neutrino detectors also play an important role in the emerging "multi-messenger" astronomy field. As far back as Supernova SN1987A, observations of neutrinos from cosmological events have proven valuable for both understanding astrophysical processes and studying fundamental particle properties. Multi-messenger astronomy includes observing phenomena in carefully time-synchronised optical and radio-frequency telescopes, gravitational wave detectors, and neutrino experiments. The neutrino experiments are particular important for understanding supernovae. A number of the projects discussed in this document are important contributors to this field, including SNO+, HALO/HALO-1kT, Hyper-K, IceCube, DUNE, and P-ONE.

Note that other future large projects are also under consideration in the international milieu, such as the Future Circular Collider and the proposed massive Liquid Argon dark-matter detector ARGO. R&D for future projects is an important part of the Canadian particle physics program.

From this information it is evident what the community is focused on: searches for evidence of new physics at or above the TeV scale; searches for dark matter or dark sector particles in various ways; measurements of the neutrino mixing angles; searches for differences in the properties of matter vs. antimatter beyond the SM in both the lepton and quark sectors; and searches for lepton number violation in neutrinoless double beta decay. As measured by the fractions of time people are dedicating to particular projects it is evident that the IPP community would like to address each of those questions. Because of the nature of the questions and experiments, the program has a mixture of large projects that have a program of a range of physics to explore and smaller projects that are focused on a single or small number of physics questions. In terms of priorities of existing IPP projects, projects of the highest priority are those where the potential for a major discovery is significant and advances in the field are certain; many in our community are investing the majority of their research time and effort into the project, have a significant impact on the experiment and where substantial Canadian investments have already been made; the project is well managed and there are sufficient resources to achieve the scientific goals and every expectation that the project will deliver the science in a timely manner.

3 Theoretical Particle Physics

Theoretical particle physicists build consistent mathematical descriptions of the fundamental components of the Universe. Such descriptions are essential to understanding experimental data and observations, and they guide new experimental searches. Developments in particle theory are also valuable in their own right, revealing new and surprising connections between seemingly unrelated phenomena or research disciplines.

Theorists in Canada work on a very wide range of topics and try to answer all of the "Big Questions" mentioned previously, from the dynamics of the strong force to the origin of dark matter to the nature of quantum gravity. The research product of the theory community is diverse and can include:

- **Precise predictions** for the Standard Model (SM) and beyond. These very challenging calculations are essential to testing the SM with experimental data and searching for new physics beyond it.
- **New theoretical methods** to better understand quantum field theory. The language of particle physics is quantum field theory, but this language is still being deciphered. Discoveries in quantum field theory enable more precise calculations in particle physics and other fields, and are of great mathematical interest in their own right.
- **New theories** that address deficiencies of the SM. Theories that go beyond the Standard Model (BSM) attempt to explain the mysteries and unresolved experimental shortcomings of the SM such as neutrino masses, dark matter, and origin of electroweak symmetry breaking.

- **Proposals for new experiments and techniques**. Theories that extend the SM often predict new signals that motivate novel search techniques at existing experiments and new experimental approaches in the future. In many cases, theorists are helping to drive the next generation of experiments as well as expand the scientific output of the current experimental program.
- **Developments in quantum gravity**. A full quantum mechanical understanding of gravity is still in progress. Recent advances in the field have provided new insights into the nature of spacetime and cosmology as well as new connections with quantum information and computing.

In this section we describe the broad research program of theoretical particle physics in Canada, and we give an overview of the community together with its role in HQP training and the resources it requires.

3.1 Research Goals

Theoretical particle physics research in Canada spans a broad range of topics and techniques. Some theorists work closely with experimental data by making predictions for future experiments or developing new theories to address observational puzzles. Others study more formal topics, such as the structure of quantum field theories or the properties of quantum gravity. Both approaches are essential components of a healthy particle physics community.

A major research goal of particle physics theory is to test the SM and discover what lies beyond it. Precision theoretical calculations within the SM have been confirmed by a wide range of experimental data. Even so, there are multiple observations that demonstrate the necessity of BSM physics: the presence of dark matter (DM) that seems to be required by cosmological and astrophysical observations, the cosmological excess of matter over antimatter in the observable universe, and the discovery of neutrino oscillations over a wide range of energies and distances.

Dark matter is a leading research topic of Canadian theorists, both in terms of building models for potential DM candidates and in computing and predicting signals that DM could leave in different kind of experiments. Indeed, DM could be created and observed in accelerator-based experiments; ambient DM could produce signals in direct detection experiments; and DM could be detected indirectly via annihilation or decay into SM particles via the observation of astrophysical gamma-rays, cosmic rays, or neutrinos. Theoretical studies of such signals are helping to guide the search for dark matter, as well as opening new search directions such as gravitational wave astronomy and a wide range of cosmological observations.

In various DM models, the DM is part of a larger dark sector containing light states (the DM itself and/or some mediator) that couple very weakly to the SM. Generically, such very light, feebly-coupled particles are difficult to detect at colliders, so other experimental techniques may be better suited for this task. Theorists are actively exploring how such light dark matter and related dark-sector particles could be detected at neutrino experiments, meson factories, and beam-dump or fixed target experiments.

Theory research is also helping to drive experimental searches for dark matter by motivating promising search targets, devising techniques for existing experiments that could open new avenues for discovery, and even proposing new experiments. Two examples of the last with major participation from Canadian theorists are LDMX, which is currently in the design study phase, and MATHUSLA which is discussed further in section 5.6. Theorists typically remain involved in these experiments collaborating with experimentalists through all phases from design through the data analysis. Examples of new analyses with Canadian origins include searches for self-destructing dark matter at Super-K, Borexino, SNO+, and DUNE, searches for Emerging Jets at the LHC, and searches for mirror baryons in Large Scale Structure observations. Theorists are also working with established experimental collaborations to bring these analyses to fruition.

Another cosmological observation that points to the existence of new physics beyond the SM is the excess of matter over antimatter in the form of a baryon-antibaryon asymmetry. To explain the origin of the asymmetry in the early universe, a mechanism of baryogenesis is needed with the essential ingredients of baryon number violation, C and CP violation, and a departure from thermodynamic equilibrium. These requirements are present in the SM but they do not appear to be sufficient to account for the observed matter asymmetry. This then motivates new physics and correspondingly new signals in experiments. For example, specific theory proposals for baryogenesis predict a wide variety of observable effects, including deviations in Higgs boson decays, new sources of quark and lepton flavour mixing and CP violation, enhanced rates of nucleon decay, and potential connections to dark matter. Theoretical developments are also being pursued to provide more precise predictions of the matter asymmetry in specific theories.

Neutrino oscillations demonstrate that these particles have mass, which in turn requires new physics beyond the (renormalizable) SM. This motivates theoretical investigations of potential sources for the neutrino masses and mixings. These studies have found promising connections with dark matter and the matter asymmetry, and motivated new signals at the HyperK, DUNE, the LHC, and in lower-energy precision experiments such as neutrinoless double beta decay. Some theories of neutrino mass also address the unexplained hiearchy in mass among the charged leptons and quarks of the SM. Neutrinos can have important effects on cosmology and astrophysics, and theorists are investigating these connections as well as new ways to use neutrinos as a tool to probe dark matter.

One of the leading questions in particle physics over the past half century is the origin of electroweak symmetry breaking. The experimental discovery of the Higgs boson, long after its existence was predicted theoretically, reframes this question but does not fully answer it. Theorists have been very active in proposing ways to test whether this new particle is the same as the one predicted by the SM using data from the LHC and beyond. The corresponding existence of a fundamental scalar Higgs particle also sharpens the puzzle of naturalness of the electroweak sector. Our expectation based on quantum field theory is that it is extremely unlikely for the Higgs boson to be so much lighter than other seemingly fundamental quantities such as the Planck mass unless new BSM physics is present. Many specific candidates have been built by theorists including supersymmetry, composite Higgs, and extra spatial dimensions. Theorists also use existing experimental data to constrain such theories and predict how they could be tested with future measurements or experiments. A common feature of most of these theories addressing electroweak naturalness is the existence of new particles that could be discovered at the LHC or its successors.

Precision calculations within the SM are required to test the theory and to look for new phenomena that might lie beyond it. Theorists in Canada are involved in a range of such calculations using a range of techniques. In many cases, calculations can be done perturbatively but become very complex and technically challenging if a high degree of precision is required. Different approaches are required when the underlying physics is strongly interacting, such as processes involving the strong force (QCD) at lower energies. A powerful method in this context is direct numerical simulation of theories using a discrete lattice approximation of spacetime. Modern calculations in lattice field theory often require the use of large computer clusters and the contributions of many people within large collaborations (by theory standards). A major focus of lattice calculations are quantities in QCD, such as untangling the surprising spectrum of exotic hadrons that emerged from recent experiments. Lattice calculations also provide results that are widely used in flavour physics, as well as inputs that are very useful for computing the anomalous magnetic moment of the muon ($(g-2)_\mu$), rates of dark matter detection, and determinations of α_s. In addition to difficult numerical computations, work in lattice field theory is also pursuing new approaches and applications such as calculations with chiral fermions or supersymmetry where the standard techniques do not work.

Quantum field theory is the foundation on which the SM is built. By studying the detailed structure of quantum field theories, theoretical particle physicists aim to find better methods to compute observables as well as build a deeper understanding of the fundamental constituents of Nature. These investigations have revealed surprising new connections between seemingly unrelated theories and new techniques to calculate at both weak and strong coupling. Some of the most important recent progress on the study of strongly coupled field theory has involved the so-called "conformal bootstrap" approach, where analyticity and unitarity constraints are used to extract information about quantum field theories even in the absence of a traditional perturbative expansion. Related ideas have been used to study scattering amplitudes in a range of theories, yielding new insights into underlying geometric structures and possibly even the nature of spacetime as well as practical methods for doing calculations in QCD and gravity. A notable feature of these approaches is that they rely on deep and growing links between the formal and the phenomenological sides of particle theory.

Building a successful and consistent theory of quantum gravity, where the classical theory of General Relativity is extended to obey the principles of quantum mechanics, is one of deepest and hardest challenges in physics. String theory is the leading candidate for such a theory, and postulates that the fundamental objects of the theory have a finite extent. This approach is a very rich and mathematically sophisticated framework containing many aspects such as extra dimensions, branes, various kind of gauge fields, and of course strings. Enormous progress in string theory in recent years has led to a much deeper understanding of the structure of quantum gravity, as well as new results and applications in pure mathematics, formal quantum field theory, QCD, condensed matter physics, and quantum information. String theory has also provided guidance for where to look for new physics beyond the SM. For example, extra dimensions have been used to address to hierarchy problem and the flavour problem.

A major result originating from string theory is the AdS/CFT correspondence, which relates certain (string) theories in anti-de-Sitter (AdS) spacetime to conformal field theories (CFT) in a lower number of dimensions. This duality between seemingly unrelated theories is one of the most important discoveries in particle theory in the last 25 years. It has led to an enormous body of theoretical work, including the study of black holes, condensed matter systems, composite Higgs theories, and the hydrodynamics of the quark-gluon plasma produced in heavy ion collisions at RHIC and the LHC.

One of the greatest successes of the AdS/CFT correspondence and string theory is the physics of black holes. Using these methods, a detailed calculation of black hole entropy in terms of string micro-states was obtained in 1996. Since then, further work using AdS/CFT has led to enormous progress on the black hole information paradox. An important offshoot of this work is a deeper understanding of quantum information, with potential applications to quantum computing and beyond.

Particle physicists also address questions in cosmology that connect formal theory to observations. There is now significant evidence for the idea cosmic inflation where the universe underwent exponential expansion at very early times. There are many models of inflation, and building predictive models that are consistent with cosmological observations is an active area of research. While these models can be described by quantum field theories, sensitivity to higher dimension operators makes understanding inflation within string theory or other theories of quantum gravity important. String theory contains many fields which are expected to be much lighter than the string scale, such as axions and moduli, and those fields can have consequences for cosmology, including serving as an inflaton field. In general, the bridge between cosmology and string theory, including models for inflation and other new scenarios for early universe cosmology, as well as cosmological tests of quantum gravity, are topics that theorists have been exploring. Indeed, while in most models the string scale is far too high to be accessible to terrestrial experiments, string theory or other theories of quantum gravity might leave their imprint in early universe cosmology.

Finally, theorists are interested in studying dark energy, which makes up most of the energy of the universe but is nevertheless incredibly small compared to the simplest estimates from quantum field theory. Is dark energy explained by a cosmological constant, a single number in the Lagrangian of General Relativity? If so, why is that number so small? If not, what are the more complicated dynamics that give rise to dark energy? And how can those dynamics be probed? Like the physics of black holes, this cosmological constant problem lies precisely at the intersection of gravity and quantum field theory. Members of the Canadian particle theory community are tackling these problems using approaches from theories of quantum gravity, including extra dimensions in string theory.

3.2 Community Overview

Particle theorists in Canada work in universities, national laboratories, and research institutes across the country. Tenured and tenure-track theory faculty make up roughly a third of the IPP membership, with about 50 of these members receiving a Discovery Grant from the SAPES envelope. These faculty work with and train a larger number of undergraduate and graduate students and postdoctoral researchers. The list of IPP members who do theory is given in Table 1, along with the subject of their individual research using the categories of the arXiv.

Faculty positions in theoretical physics in Canada attract top talent from all over the world. A typical faculty position will receive well over one hundred applicants with candidates from many of the top institutes in the world such as CERN and Harvard, and many of the faculty are not originally from Canada. The international nature of the Canadian community facilitates collaboration with scientists abroad, and it also speaks to the high quality of the Canadian groups that some of the most successful researchers in the world choose to come to here.

Relative to typical experiments in particle physics, theorists tend to work in smaller groups on projects with a shorter time scale (but that may be part of a longer-term research program). Many theorists also cover a variety of subfields and disciplines. For example, theorists studying dark matter often also make predictions for searches at the LHC or investigate connections with astrophysics. As outlined above, the research pursued by the community spans a range of topics and approaches. This diversity is a strength of the community, and has lead to several projects leveraging this breadth of expertise.

Theoretical research is highly collaborative, and theorists in Canada work extensively with each other and with international partners. There are several regional centres where theorists from nearby universities frequently collaborate. One example is the Atlantic Theory group which has been particularly successful at getting undergraduate students involved in research and has regular workshops giving them the opportunity to present their work. Across the community, the collaboration is fostered by IPP fellowships as well as visitor programs and workshops at the Perimeter Institute, the McDonald Institute, and TRIUMF. The CAP Division of Theoretical Physics (DTP) also connects theorists across multiple physics disciplines. International collaboration relies strongly on travel to workshops and conferences for Canadian researchers to share their results and develop new partnerships.

Collaboration between experimentalists and theorists is crucial for the progress of the field as a whole. Many theorists in Canada work closely with experimentalists, both within Canada and beyond, and these connections provide important guidance for experimental searches and future experiments. In some cases, Canadian theorists have participated in and helped to develop experiments themselves.

The Perimeter Institute (PI) plays a large role in the Canadian particle theory community seven members of the IPP being fully based at PI or jointly appointed between PI and a partnering university. These theorists have reduced or no teaching duty, allowing them to devote more time to research. In addition to faculty, PI also hires 2-3 theory postdocs in each of the subfields where they have active research efforts, including particle phenomenology, quantum gravity, and quantum field theory. Many theorists from across the country also connect with PI through affiliate appointments, which allow them to visit the institute and collaborate with its members on a regular basis.

Theoretical research in astroparticle physics has grown significantly over the past few years through the establishment of the Arthur B. McDonald Canadian Astroparticle Physics Research Institute (MI) in 2015. The MI catalyzed the hiring of three new theory faculty at Canadian universities, and currently supports approximately 10 postdocs and 14 graduate students at universities across the country. While the salaries of the faculty are guaranteed into the future, funding to support students, postdocs, and research expenses will need to transition to the SAPES envelope in the coming years which may lead to increased funding pressure.

Name	Institution	Subject
Mohammad Ahmady	Mount Allison	hep-ph
Aleksander Aleksejevs	Memorial	hep-ph, hep-th
Jonathan Bagger	TRIUMF	hep-th
Svetlana Barkanova	Memorial	hep-ph, hep-th
Ian Blokland	Alberta	hep-ph
Vincent Bouchard	Alberta	math-ph
Nassim Bozorgnia	York	astro-ph, hep-ph
Joe Bramante	Queen's/PI	hep-ph
Robert Brandenberger	McGill	astro-ph, hep-th
Alex Buchel	Western/PI	hep-th
Cliff Burgess	McMaster/PI	gr-qc, hep-ph, hep-th
Bruce Campbell	Carleton	hep-ph
Margaret Carrington	Brandon	hep-ph, hep-th
James Cline	McGill	hep-ph
Gilles Couture	UQAM	hep-ph
David Curtin	Toronto	hep-ph
Andrzej Czarnecki	Alberta	hep-ph
Keshav Dasgupta	McGill	hep-th
Rainer Dick	Saskatchewan	hep-ph
Mariana Frank	Concordia	hep-ph
Andrew Frey	Winnipeg	hep-th
Steve Godfrey	Carleton	hep-ph
Jaume Gomis	PI	hep-th
Thomas Gregoire	Carleton	hep-ph
Derek Harnett	Fraser Valley	hep-ph
Bob Holdom	Toronto	gr-qc, hep-ph
Calvin Kalman	Concordia	ed-ph
Pat Kalyniak	Carleton	hep-ph
Joanna Karczmarek	UBC	hep-th
Gabriel Karl	Guelph	hep-ph
Achim Kempf	Waterloo/PI	gr-qc, quant-ph
Nikolay Kolev	Regina	hep-ph
Pavel Kovtun	Victoria	hep-th
Helmut Kroeger	Laval	hep-lat, hep-th
Gabor Kunstatter	Winnipeg	gr-qc, hep-th
Randy Lewis	York	hep-lat, hep-ph
Heather Logan	Carleton	hep-ph
David London	Montréal	hep-ph
Michael Luke	Toronto	hep-ph
Richard MacKenzie	Montréal	hep-ph, hep-th
Alexander Maloney	McGill	hep-th
Kim Maltman	York	hep-lat, hep-ph
Rob Mann	Waterloo/PI	gr-qc, hep-th
Luc Marleau	Laval	hep-ph
Pierre Mathieu	Laval	hep-th, math-ph
David McKeen	TRIUMF	astro-ph, hep-ph
Vladimir Miransky	Western	cond-mat
Nader Mobed	Regina	gr-qc, hep-th
John Moffat	Waterloo/PI	gr-qc
M. de Montigny	Alberta	gr-qc
David Morrissey	TRIUMF	hep-ph
Robert Myers	PI	hep-th
John Ng	TRIUMF	hep-ph
Rachid Ouyed	Calgary	astro-ph, nucl-th
Manu B. Paranjape	Montréal	cond-mat, gr-qc, hep-th
AW Peet	Toronto	hep-th
Alexander Penin	Alberta	hep-ph
Levon Pogosian	SFU	astro-ph
Erich Poppitz	Toronto	hep-th
Maxim Pospelov	Victoria/PI	astro-ph, hep-ph
Saeed Rastgoo	York	gr-qc
Adam Ritz	Victoria	hep-ph
Moshe Rozali	UBC	hep-th
Ruben Sandapen	Acadia	hep-ph
Gordon Semenoff	UBC	cond-mat, hep-th
Kris Sigurdson	UBC	astro-ph
Rafael Sorkin	PI	gr-qc, hep-th
Tom Steele	Saskatchewan	hep-ph
Daniel Stolarski	Carleton	hep-ph
Sean Tulin	York	astro-ph, hep-ph
Mark Van Raamsdonk	UBC	hep-th
Aaron Vincent	Queen's	astro-ph, hep-ph
Peter Watson	Carleton	hep-ph
Richard Woloshyn	TRIUMF	hep-lat
Yue Zhang	Carleton	hep-ph
Ariel Zhitnitsky	UBC	astro-ph, hep-ph

Table 1: Theory members of the IPP. Subject is the arXiv category(ies) of the majority of recent work.

3.3 Theory HQP and Societal Impact

Students and postdoctoral researchers form an integral part of the Canadian theory community. Their contributions are essential in driving the research programs of faculty. In doing so, they also develop the skills that are needed to thrive in both academia and the knowledge-based economy.

The vast majority of the grant funding that goes to theorists is for support of HQP. Faculty holding grants typically supervise 1-3 graduate students who then collaborate with more senior researchers, professors and postdocs, and are co-equal authors on the research they produce. Not all students continue in the field, but all learn a diverse array of quantitative skills that can be applied to many types of job outside academia should they choose not to continue in physics. Graduate students typically give seminars and talks at conferences that give them exposure in the community, allow them to form new collaborations, and can tremendously enhance future job prospects. An example of a recent graduate student who has gone on to a faculty position is Claudia Frugiuele who received her PhD at Carleton in 2012 and started a faculty position at INFN, Sezione di Milano in Italy in 2020.

Postdocs are among the most productive researchers in the field as they have substantial experience and knowledge but do not have the external time commitments of faculty members. Most theory grants are insufficient to support postdocs, so theorists at the same university typically pool grant funds to hire postdocs. As mentioned above, postdocs often work with graduate students, thereby contributing to the training of HQP in their own right, which can be very positive when applying to faculty positions. Travel to give seminars and attend conferences is crucial for postdocs so they can attain international recognition, a necessary step to obtaining a faculty position. A recent success story is Djuna Croon who is currently completing a postdoc position at TRIUMF and will begin a faculty position at Durham in the UK in 2021.

While most travel is funded by supervisor grants, there are a few additional opportunities for travel. The IPP recently inaugurated the Early Career Theory Fellowship that funds short and medium term collaborative visits abroad for postdocs and senior graduate students. The first round funded two visits to the United States and one to Denmark, and the program will continue as soon as COVID-19 allows. The MI also funds exchanges for both students and more senior scientists that can be accessed by theorists.

It is very beneficial for graduate students to attend summer schools where they can be exposed to a wide variety of expertise. PI and TRIUMF both play a crucial role in Canada in that respect. TRIUMF holds annual particle theory workshops, and PI has frequent workshops on a variety of topics. TRIUMF also holds an annual Summer Institute aimed at theory and experimental graduate students, and jointly with PI and SNOLAB organizes the Tri-Institute Summer School on Elementary Particles (TRISEP), which also receives IPP sponsorship.

The HQP supervised by Canadian particle theorists obtain skills that are extremely useful beyond just research in physics. As part of their training, graduate students and postdocs develop the ability to analyze and quantitatively model complicated systems along with computational expertise and a scientific approach to problem solving. These are vital tools in today's economy. Indeed, most graduate students and postdocs transition to fields outside of academic physics in government or in the private sector in fields such as data science, medicine, high technology, and education.

3.4 Required Resources

In FY2020, the subatomic theorists (including nuclear) received in the form of Discovery Grants about 11% of the overall SAPES envelope which is a decrease from 13% in each of the previous three years, and lower than the 15% average cited in the 2016 LRP. Grants need to be sufficiently large so that theorists can afford to hire graduate students and postdocs. Furthermore, the international competition to hire the best theory postdocs is very fierce, and Canadian theorists need to remain competitive in what they can offer, in terms of salary, travel budget and the duration of the appointment. Having outstanding theory postdocs not only ensures the highest levels of excellence in the science, but also ensures the research environment for graduate students is at the highest level.

In this community, faculty members' capacity to train more students and postdocs is limited solely by funding. For example, at McGill, there are typically more than 100 applicants for graduate student positions in particle theory and funding constraints allow acceptance of at most 10. At small universities, this is an even more acute problem as NSERC grants for researchers in those institutions are systematically smaller. For example, at Univeresity of Winnipeg, there are currently 16 applicants for a single position. Increases in funding to discovery grants in theory will directly increase the number and quality of highly qualified personnel being trained in Canada.

Computing is also a necessary tool for theory research including Monte Carlo simulations and precise calculations. The lattice field theory groups need substantial computing resources, and other members of the community also have computing needs. Many of the more modest computing demands are serviced by local clusters paid for by universities, NSERC, and CFI, with the larger users also needing resources Compute Canada (and NDRIO in the future).

Travel to conferences and workshops and to give seminars is a critical tool for theorists to share their research and start new collaborations. Domestic travel allows different theorists to share their expertise with one another and more funding would increase the synergy of the Canadian community. HQP travel is also essential for them to build their profile in the field, especially those students and postdocs at smaller or geographically isolated institutions. Finally, support to organize workshops, conferences and summer schools where theorists can meet and exchange ideas is essential to ensure excellence in the field. PI, TRIUMF and other partners are playing a critical role in this regard.

4 IPP Projects

4.1 ATLAS

ATLAS is one of the two general purpose detectors designed to study high-energy proton-proton collisions at the Large Hadron Collider (LHC) at CERN. Data taking began in 2009, with first high-energy running at a centre-of-mass energy of 7 TeV in 2010. The Run-1 dataset was collected at 7 TeV in 2010 and 2011 and at 8 TeV in 2012, with integrated luminosities of about 45 pb^{-1}, 5 fb^{-1} and 20 fb^{-1}, respectively. This Run-1 dataset that was used for the discovery of the Higgs Boson, announced in 2012. The centre-of-mass energy was increased to 13 TeV for Run-2, which began in mid-2015 after a two-year long shutdown (referred to as LS1). ATLAS operated in Run-2, until December 2018, with instantaneous luminosities in excess of 2×10^{34} $cm^{-2}s^{-1}$ and total integrated luminosity of 149 fb^{-1} recorded by ATLAS.

The LHC and ATLAS entered a second long shutdown, called LS2, in 2018 in order to upgrade the accelerator to to deliver twice the LHC design luminosity, and to upgrade the ATLAS and CMS detectors. Canada is contributing to the upgrade of the LAr calorimeter trigger system and the construction of the New Small Wheels (NSW) of the muon system. This shutdown is expected to end in 2021 with the resumption of operation for Run-3. It is expected that the LHC will deliver approximately 300 fb^{-1} during Run-3, tripling the size of the data set collected at 13 TeV center-of-mass energy. A third long shutdown (LS3) will begin around 2025 to upgrade the LHC and ATLAS for the High Luminosity LHC (HL-LHC) era.

4.1.1 Research goals

The LHC is an energy-frontier machine and the ATLAS experiment is designed to explore many of the most important scientific questions of our time. One main goal of the LHC experimental program is to elucidate the long-standing issue of the nature of electroweak symmetry breaking. The 2012 discovery of the Higgs boson goes some way towards addressing this goal, but investigations of the properties of this boson continue. Many other questions also remain unanswered and could be investigated with existing data or in future runs of the LHC. For example, arguments related to naturalness and the hierarchy between the weak scale and the Planck scale motivate a belief that there must be new physics in the energy range accessible at the LHC. In addition, cosmological observations tell us that a large portion of the mass in the universe is in the form of dark matter (DM), with normal baryonic matter accounting for only a small fraction. Dark matter is not accounted for in the Standard Model (SM) but it might be produced at the LHC. Furthermore, because of its versatility, the ATLAS experiment is able to detect, directly or indirectly, a large variety of new particles and new forces that might be present beyond the Standard Model (BSM).

The ATLAS experiment has already had a profound impact on particle physics through the discovery, along with the CMS experiment, of the Higgs boson. This resulted in the awarding of the 2013 Nobel Prize to Peter Higgs and Francois Englert, with the ATLAS and CMS collaborations being specifically mentioned in the Nobel Citation. This was recognized as a landmark achievement for Canadian science in the federal government's 2014 Science and Technology Strategy document "Seizing Canada's Moment: Moving Forward in Science, Technology and Innovations 2014". Following this success, further studies of the properties of the newly discovered boson have so far shown these to be consistent with SM expectations. However, additional work using future datasets will be required to establish that this is indeed the single Higgs boson predicted by the SM and not part of an extended Higgs sector such as is predicted in many theories of BSM physics. Run-2 Higgs boson studies have enabled observation of all of the main production modes, as well as of decay modes that were not accessible using Run-1 data. New results based on the full Run-2 dataset include the observation (at 5.2σ) of $t\bar{t}H$-production followed by H$\rightarrow \gamma\gamma$ decay. These and other measurements are expected to improve as the size of the dataset is increased. However, measurements of some quantities, such as the couplings to second-generation fermions, will require larger datasets, while others, such as the Higgs self-coupling, may only be possible with the very large dataset expected to be collected over the full operations period of the HL-LHC. The Higgs self-coupling is a particularly important measurement: this parameter can reveal the shape of the Higgs potential, testing whether electroweak symmetry in nature occurs via the simple mechanism posited by the SM, or some more complicated dynamics. The shape of the potential can also have important consequences for early-universe cosmology. The HL-LHC will likely provide the best constraints on this coupling until the next high-energy collider is constructed.

In addition to studying the Higgs and probing the Standard Model in a new energy regime, the LHC will look for a variety of BSM physics, the most well-known probably being supersymmetry. In supersymmetric models with R-parity conservation, the lightest supersymmetric particle is often a stable, electrically neutral, weakly-interacting massive particle (WIMP) with properties making it an excellent dark matter candidate. This is just one example of the type of BSM physics that will continue to be investigated in future LHC running. Others include theories invoking the existence of extra dimensions, composite quarks or leptons, composite Higgs, additional gauge sectors (with high-mass gauge bosons sometimes referred to as W' and Z') or other new particles, such as vector-like quarks. In recent years ATLAS has been increasingly investing in a systematic approach to searches for new long-lived particles that may have gone undetected until now. This will provide additional new opportunities for discovery.

The LHC is likely to remain at the high-energy frontier for at least the next two decades, so may provide for the only direct searches for such BSM physics over this time period, though indirect searches via precision measurements will be done also at other facilities. As such, the LHC experiments are crucial to the future of the field, and it is thus very important to ensure that the detector performance is maintained (or even improved, where feasible) as the LHC luminosity is increased to well above the original design value. This is the goal of the ATLAS upgrade program, in which Canadians are playing significant roles.

4.1.2 The Canadian team and its impact

The ATLAS-Canada collaboration, currently comprises 43 NSERC grant-eligible faculty-level investigators at ten institutions, contributing 39 FTE, as listed in Table 2. ATLAS-Canada currently employs about 35 RAs, who are mainly funded by NSERC with some technical positions funded wholly or partially through CFI awards. RAs play a key role within ATLAS-Canada and often take leadership roles in the ATLAS collaboration that, in recent years, include LAr calorimeter run-coordinator, silicon tracker (SCT) run-coordinator, LAr DQ convener, overall ATLAS DQ convener, Distributed Computing Integration and Commissioning Co-coordinator, Offline Reprocessing coordinator, Prompt Reconstruction Coordinator, NSW software coordinator, LAr Phase-2 Upgrade Firmware Coordinator and ITk Strips Activity Coordinator, and a seat on the Collaboration Board Advisory Group. Students also play an essential role in all aspects of the ATLAS-Canada research efforts. The number of graduate students is around 80 and 75% are in PhD programs. It is expected that HQP training will continue at the same level or have moderate increases due to the upgrade projects out to 2027.

Canadians have contributed to many of the different hardware systems that make up the ATLAS detector, including the calorimeters, tracking detectors, and detectors used for beam-background monitoring, luminosity determination and forward physics. This reflects the broad interest and expertise of the large ATLAS-Canada collaboration. Canadians have also played significant roles in the development of both grid-computing and cloud computing software tools.

Phase-1 upgrades to the ATLAS detector are currently in progress. ATLAS-Canada is working on the upgrade of the LAr calorimeter trigger system and the construction of the New Small Wheels (NSW) of the muon system, funded via a CFI award in the 2015 IF competition. ATLAS-Canada is responsible for the design, testing and production of new front-end-crate baseplanes for the Hadronic Endcap Calorimeter. ATLAS-Canada is also playing a leading role in the construction of small thin-gap-chambers (sTGC) for the NSW. The baseplane project has been successfully completed. The NSW continues with high priority and the goal that both NSWs will be installed during LS2, though contingency plans are also being developed.

Installation of the Phase-2 upgrades will not begin until 2025, but work on these more substantial upgrades is now in full swing. Technical Design Reports (TDRs) were produced and approved in 2018 and negotiations with ATLAS Funding Agencies were largely concluded with the signing of MOUs in 2019. The Canadian contributions to the Phase-2 upgrades are being funded by a CFI IF awarded from the 2017 competition, and will be accompanied by a Canadian contributions to the accelerator upgrade funded via an award from the federal government (announced by then Science Minister Kirsty Duncan in June 2018) and an in-kind contribution from TRIUMF, which will manage the accelerator upgrade work, that will be carried out in collaboration with Canadian industry. Canada's

Phase-2 projects include contributions to upgrades of the on-detector and off-detector readout electronics of the LAr calorimeter, including firmware, and to the construction of a new all-silicon inner tracking detector called the ITk. The latter project, in particular, is an enormous undertaking involving almost half of the ATLAS collaboration, representing over 40% of the total Phase-2 upgrade costs. ATLAS-Canada has established production sites for components of the silicon-strips system in both eastern and western Canada and are involving industry in a number of aspects of the project.

The ATLAS-Canada group makes significant contributions to many ATLAS measurements, including the measurement of Higgs properties, and Standard Model measurements. ATLAS-Canada is also active in searches for physics beyond the Standard Model, including searches for SUSY particles, new resonances, heavy Higgs-like particles, vector-like quarks, quantum black holes, magnetic monopoles and new long-lived particles. Since 2015, ATLAS-Canada members have served in leadership roles of ATLAS Physics groups including: Top, Higgs, Exotics and Upgrade Physics, as well as a term as ATLAS Physics Coordinator.

4.1.3 Required resources

CERN-based ATLAS infrastructure is funded by the participating nations via a Maintenance & Operations fund to which each contributes annually, in proportion to their fraction of PhD-holding scientific authors. This follows terms set out in an MOU that covers the construction and operation of the detector, with addenda for the various upgrade phases, most recently those signed in 2019 for the Phase-2 upgrades. The annual Canadian M&O contribution of about $1M is paid from the NSERC Operating grant.

In Canada, equipment and hardware infrastructure needs are related mainly to the upgrade projects and are supported from CFI awards. The ATLAS Canada group benefits in various ways from MRS-funded personnel at a number of Canadian institutions, and from the support of TRIUMF, which hosts part of the infrastructure for Canada's contributions to the ITk, and is also involved in the New Small Wheel project and both the Phase-1 and Phase-2 upgrades to the LAr calorimeter. Since CFI awards for these ugrade projects have been secured, it is not expected that there will be significant new detector-related equipment or infrastructure requests during the 2022-2026 time period. Continued operating support from NSERC will be critical, and may require increases reflecting growth in the collaboration.

ATLAS-Canada computing needs are funded via CFI awards that support the ATLAS Tier-1 computing centre, which was recently relocated from TRIUMF to SFU, as well as shared resources supplied through Compute Canada. For computing, periodic hardware refreshes to the Tier-1 will be needed and it is expected that further funding requests will be submitted to CFI, in addition to a request in the 2020 CFI-IF competition.

As members of the Worldwide LHC Computing Grid (WLCG) ATLAS-Canada is required to pledge resources annually to the experiment; these form the bulk of the resources referred to above. Canadians also play a leading role in the use of cloud computing for high-energy physics (not just for ATLAS). That work has also been funded by CFI, through CyberInfrastructure awards. It is anticipated that there will be further requests for support of this program in the coming years, though there are no future CyberInfrastructure competitions planned, so this funding may need to be sought from other sources. Details of future Tier-2 and Tier-3 computing, which is based on shared resources, will depend on the details of Canada's new digital research infrastructure organization, that will replace Compute Canada.

The ATLAS-Canada computing requirements are based on the overall ATLAS requirements. There are ten Tier-1 computing facilities in ATLAS, including one in Canada that contributes 10% of the Tier-1 CPU, disk, and tape. Since Canada represents roughly 5% of the ATLAS collaboration, our Tier-2 facilities contribute that fraction of the ATLAS Tier-2 CPU and disk. In addition, we double the CPU and add 15% to this disk contribution to allow for Canadian-only Tier-3 resources, and beyond-pledge ATLAS credits.

Projections of ATLAS computing requirements and annual hardware improvements at a sustained investment level indicate that ATLAS computing needs can be met out to 2027. Beyond 2027, there will be significant challenges to meet the computing requirements, and mitigation strategies are being investigated by the LHC experiments.

4.1.4 Outlook for the period 2027-2036

Envisaged operations period of the HL-LHC corresponds closely to the 2027-2036 time period. This period will be largely dedicated to the operation of the LHC and ATLAS with the target of collecting 3000-4000 fb^{-1} for physics

Name	Institution	FTE
Justin Albert	Victoria	0.5
Jean-Francois Arguin	Montréal	1.0
Georges Azuelos	TRIUMF/Montréal	1.0
Alain Bellerive	Carleton	0.9
Francois Corriveau	IPP/McGill	0.8
Claire David	York	0.5
Matthias Danninger	SFU	1.0
Colin Gay	UBC	1.0
Dag Gillberg	Carleton	1.0
Douglas Gingrich	TRIUMF/Alberta	1.0
Kevin Graham	Carleton	0.7
Jesse Heilman	Carleton	1.0
Nigel Hessey	TRIUMF	1.0
Nikolina Ilic	IPP/Toronto	0.9
Richard Keeler	Victoria	1.0
Thomas Koffas	Carleton	0.9
Robert Kowalewski	Victoria	0.5
Peter Krieger	Toronto	1.0
Michel Lefebvre	Victoria	1.0
Claude Leroy	Montréal	1.0
Alison Lister	UBC	1.0
Jean-Pierre Martin	Montréal	0.5
Robert McPherson	IPP/Victoria	1.0
Dugan O'Neil	SFU	1.0
Gerald Oakham	Carleton	1.0
Robert Orr	Toronto	1.0
James Pinfold	Alberta	0.7
Steven Robertson	IPP/McGill	0.5
Pierre Savard	TRIUMF/Toronto	1.0
Pekka Sinervo	Toronto	0.8
Randy Sobie	IPP/Victoria	0.7
Oliver Stelzer-Chilton	TRIUMF	1.0
Bernd Stelzer	SFU	1.0
Max Swiatlowski	TRIUMF	1.0
Reda Tafirout	TRIUMF	1.0
Wendy Talyor	York	1.0
Richard Teuscher	IPP/Toronto	1.0
Isabel Trigger	TRIUMF	1.0
William Trischuk	Toronto	1.0
Brigitte Vachon	McGill	1.0
Michel Vetterli	TRIUMF/SFU	1.0
Manuella Vincter	Carleton	1.0
Andreas Warburton	McGill	0.6
Total FTE		38.5

Table 2: Canadian grant eligible investigators working on ATLAS, with corresponding research FTEs.

analysis. Activities during this period will include the usual maintenance and repair and may include additional upgrades.

The relationship of ATLAS-Canada with international partners on ATLAS, over this period, is largely already defined, in the form of MOUs for the construction of ATLAS detector upgrades needed for operation in this era, as well as via the Canadian contribution to the accelerator upgrade, which takes the form of cryo-modules that will be used to house the crab cavities that are at the heart of the luminosity upgrade.

4.2 Belle II

Belle II is an experiment located at the SuperKEKB e^+e^- collider at the KEK laboratory, Tsukuba, Japan. SuperKEKB is an upgrade of the very successful KEKB collider, which operated from 1999 through 2010, primarily at the $\Upsilon(4S)$ resonance. The goal of SuperKEKB is to produce 40 times the peak luminosity of KEKB, and 30 times the combined integrated luminosity of the BaBar and Belle experiments.

The first colliding beam data with the full Belle II detector were recorded in spring 2019, and an instantaneous luminosity world record was set in June 2020. The operational focus has been on increasing the instantaneous luminosity, not on integrating data. Belle II plans to run through to 2030 to accumulate the full 50 ab^{-1} dataset. The new 2-layer pixel detector is expected to be installed in 2022, and a new final focus in 2026.

4.2.1 Research goals

Belle II will search for evidence of new physics in a wide range of final states that are sensitive to the effects of heavy virtual particles and where the Standard Model predictions are well understood. The measurement will include rare and forbidden decays, and asymmetries such as CP violation in B, charm and tau decays. Heavy virtual particles not included in the Standard Model, even those more massive than the collider's centre of mass energy, could produce deviations from the expected values.

The search for new physics in this indirect fashion is complementary to direct searches for new physics at the Large Hadron Collider (LHC). Ideally, measurements by Belle II will illuminate the deeper nature of discoveries at the LHC. But even in the absence of such discoveries, Belle II will be sensitive to physics beyond the direct reach of the LHC.

Belle II also has sensitivity for the possible production of particles predicted by models with a light "Dark sector". A possible signature could be the observation of single photons with no other particles visible in the detector. This is a high priority analysis with strong Canadian involvement.

The experiment will also continue the exploration of the weak force and the SM description of CP violation and CKM matrix, a program successfully followed by BaBar and Belle. The Belle II data will be essential in clarifying the values of $|V_{cb}|$ and $|V_{ub}|$, where inclusive and exclusive approaches do not agree well, and for determining whether the disagreement with the Standard Model seen in $B \to D^{(\star)}\tau\nu_\tau$ is due to new physics or to inadequate understanding of the background.

The LHCb experiment at the LHC has a similar physics program to Belle II, searching for evidence of new physics through high-statistics and high-precision heavy flavour measurements. There are measurements in which LHCb and Belle II are in direct competition, particularly in final states in which B or charm mesons decay to final states that contain only charged particles. Belle II has the edge in tau decays and in final states containing neutrinos or neutral pions. The overlap in capabilities of two experiments will be desirable if either observes new physics.

4.2.2 The Canadian team and its impact

The Canadian group consists of ten faculty at four universities for a total equivalent of 5.4 FTE (see Table 3). A large fraction of this group were previously members of the BaBar collaboration.

The Belle II group currently includes three postdocs or research associates, four PhD students, and six MSc students. Over the next three years, the number of graduate students is expected to increase to approximately 10–12, and to remain at that level at least through the early 2030's. The number of postdocs will be two or three, depending on funding.

Name	University	FTE
Hossein Ahmed	St. Francis Xavier	1.0
Christopher Hearty	IPP/UBC	0.9
Robert Kowalewski	Victoria	0.5
Janis McKenna	UBC	1.0
Steven Robertson	IPP/McGill	0.5
Michael Roney	Victoria	0.4
Randall Sobie	IPP/Victoria	0.3
Andreas Warburton	McGill	0.4
Total FTE		5.4

Table 3: Canadian investigators working on Belle II, with corresponding research FTEs for 2020. The remainder of Hearty's and Roney's research time is on the related Chiral Belle project.

Members of the Canadian Belle II group have an excellent track record of scientific accomplishments, for example with several members having been instrumental in many of the important physics results to emerge from the Babar experiment. The track record of HQP training from Canadian members of the Belle II team is strong both in terms of number and job placements. For example, over the past ten years, a total of eight postdoctoral research associates have contributed to either the Belle II, BaBar or SuperB projects, and a total of 14 PhD theses and 10 MSc theses were granted.

There are 980 collaborators from 26 countries on Belle II, including 438 PhD physicists and 354 graduate students. Currently Canada makes up 2.5% of the PhD physicists and 2.8% of the graduate students.

The Canadian group joined Belle II when construction was well underway, and so did not take on the responsibility of building part of the detector. The group joined the calorimeter subsystem. It consists of CsI(Tl) crystals, reused from the original Belle experiment, with new waveform measuring front end electronics. Canadians wrote the reconstruction code making use of the additional information, producing significantly better resolution in the presence of beam backgrounds than the original Belle algorithms. The pulse shape discrimination algorithms developed by Canadians exploit the waveforms in a unique fashion to provide hadron identification. UBC is responsible for calibration. This has a conceptual and software design component, which is still underway, plus an ongoing operational side. Victoria members wrote and maintain the GEANT detector model. The Canadian group as a whole is responsible for one-third of the calorimeter subdetector shifts, together with Italy and Russia. These are a mixture of remote and on-site. The Canadian group provided beam background shields for the endcap calorimeters. Installed into these shields are background monitors that can be used to characterize injection backgrounds. These were designed and built by U. Montreal. Canadians have also taken responsibility for the high-level trigger menu. This is a set of trigger decisions, which ultimately decides which events are saved for physics analysis or detector studies, and which are discarded.

4.2.3 Required resources

In the period 2022-2026, the Belle II team does not plan to request funds for any major detector upgrade project. They also do not anticipate use of personnel from TRIUMF or university MRS resources. The group does anticipate the occasional NSERC RTI request for in-kind contributions to the Belle II common fund. The Belle II groups anticipates a sequence of NSERC project grants to support students, postdocs and travel expenses.

The Canadian group has signed an MOU to store and process 15% of one copy of the raw data (7.5% of the total), starting in 2021. This will require a purchase of 6 PB of disk space and 50 kilo-HEPSpec06 of CPU in FY2021, and an addition 9 PB of disk space and 60 kilo-HEPSpec06 of CPU will need to be acquired in FY2024. Compute Canada has indicated that the required resources “exceed the capacity and features likely to be available through the Compute Canada allocation process”. The Canadian Belle II group has submitted a CFI application to request $2M of CFI funds to establish the Belle II data center. It will utilize cloud storage and computing technologies, and will be connected by 100 gigabit/second networks to the rest of the Belle II computing system. The Centre will be located in the Compute Canada center at the University of Victoria in order to leverage the expertise of the local group in clouds, big data and networks.

4.2.4 Outlook for the period 2027-2036

The physics goals outlined in Section 4.2.1 will require data to be collected through 2030. Based on the experience of Belle and BaBar, analysis of these data will continue through 2036. The international partners on Belle II should be reasonably stable throughout this period.

It is possible that if Chiral Belle proceeds, the run period would be extended a year or two to ensure a sufficient large polarized data set. Groups within the collaboration are studying possible upgrades to the tracking system, which could be required as the instantaneous luminosity increases. The Canadian group is not involved in these activities. Radiation damage studies by the Canadian group indicate that the calorimeter will survive with good performance through the full running period.

The requested computing resources should fulfill Canada's obligations to support central Belle II computing through the planned running period. However, an extension of the run plan could require additional resources.

4.3 DEAP-3600 (and DarkSide-20k)

DEAP-3600, an IPP Project located at SNOLAB, is a 3.3-tonne liquid argon detector used to search for dark matter by detection of scintillation light from the nuclear recoils expected in WIMP-like dark matter interactions. DEAP-3600 has operated since 2017, providing limits on dark matter using an Ar target that are complementary to measured make with Xe targets in XENON1T and LUX. After upgrades to DEAP-3600 in 2020, it is expect to operate through 2022 to acheive its ultimate sensitivity.

The next step in the "global argon dark matter" program is DarkSide-20k, which increases the fiducial mass to 20 tonnes. This detector, located at LNGS, will push the sensitivity to dark matter with mass above about 10 GeV to the neutrino floor. While this detector builds on the DEAP-3600 and DarkSide-50 projects, it is also a step towards ARGO with fiducial mass of 300 tonnes. DarkSide-20k is not yet an IPP Project.

DarkSide-20k is expected to achieve a slightly better sensitivity limit than the competing liquid xenon experiments (XENONnT, and LZ). DarkSide-20k will start data taking about 3 years after XENONnT and LZ and will be very useful should a signal be detected in liquid xenon by providing a different target mass with comparable sensitivity. Since the dependence of the cross section for the interaction of WIMPs on neutrons and protons is unknown, it will also be valuable to have a measurement with a second nucleus with different n-p ratio.

A basic design now includes an external cryostat with a design similar to that of the ProtoDUNE detector, an acrylic TPC, and an acrylic and liquid argon veto. The core of the detector is a vertical cylindrical TPC filled with liquid argon. The argon is derived from an underground source so it is depleted in 39Ar. Ionization electrons produced by charged particles traveling through the liquid are drifted in a uniform electric field towards an anode to be detected. Electrons are extracted from the liquid to a gas phase and then accelerated in a modest electric field where they excite argon atoms subsequently generating electro-luminescence photons. The electro-luminescence photons and those from scintillation in the liquid are detected by photo-detectors called silicon photo-multipliers (SiPMs) located behind the anode and cathode while the ionization electrons are collected on a transparent electrode but not explicitly detected. The electro-luminescence process is expected to yield on average 20 to 30 detected photons per ionization electron. Energy deposited in liquid argon also yields scintillation photons whose time structure can be used to discriminate against electromagnetic radioactive background in a manner similar to DEAP-3600. The barrel of the TPC is covered by reflectors coated with a wavelength shifter called TPB. TPB also covers the anode and cathode foils. Scintillation and electro-luminescence photons need to be wavelength-shifted by TPB from vacuum UV (128 nm on average) to 420 nm in order to be detected by conventional SiPMs.

DarkSide-20k will start construction in 2021 and be operational in 2023.

4.3.1 Research goals

The liquid argon dark matter program in Canada has been focusing on the DEAP-3600 experiment, achieving the best dark matter limits in liquid argon, demonstrating very low background levels, and establishing an exhaustive background model. Further upgrades to DEAP-3600 in 2020 will address backgrounds related to surface activity in the "neck" part of the detector and trace amounts of suspended particles in the argon. After the completion of these upgrades, operation to establish the background model will continue through 2021 and data taking will continue to

Name	Institution	FTE
Mark Boulay	Carleton	1.0
Bruce Cleveland	SNOLAB/Laurentian	0.2
Philippe Di Stefano	Queen's	0.6
Pierre Gorel	SNOLAB/Laurentian	0.45
Aksel Hallin	Alberta	0.66
Chris Jillings	SNOLAB/Laurentian	0.75
Szymon Manecki	SNOLAB/Laurentian	0.35
Art McDonald	Queen's	0.7
Marie-Cécile Piro	Alberta	0.2
Fabrice Retière	TRIUMF	0.25
David Sinclair	Carleton	0.3
Peter Skensved	Queen's	0.65
Simon Viel	Carleton	0.7
Total FTE		6.81

Table 4: Canadian investigators working on DarkSide-20k, with corresponding approximate research FTEs for 2020/2021.

2022. With its full exposure, DEAP-3600 will have sensitivity comparable to or better than XENON1T limits for dark matter particle masses above ∼100 GeV.

The DarkSide collaboration will build on the goals of the DarkSide-50 and DEAP-3600 experiments with DarkSide-20k. The intent is then push on to a multi-hundred-tonne detector, called ARGO. This programme will push the sensitivity for direct dark matter detection to the so-called "neutrino floor", where coherent neutrino scattering of atmospheric neutrinos becomes the dominant background.

4.3.2 The Canadian team and its impact

Canadian expertise is crucial for several key components of DS-20k. Experience with acrylic and coatings enables the Canadian group to construct an ultra low-background cryostat. They thus contribute to the TPC group and the veto group. The TRIUMF group, in collaboration with Queen's Universty, is using their experience as co-developers of the MIDAS data acquisition (DAQ) system (used also by DEAP-3600 and SuperCDMS SNOLAB, amongst many others) to design and create the DAQ. Canadians contribute to the operations and quality control of argon production, and are responsible for shipment and underground storage. Canadians are contributing to the assay of materials using germanium counting and XIA alpha counting at SNOLAB and are active members of the collaboration's Materials Group. They have used experience from developing the detailed DEAP-3600 background model to inform the design and background budget of the DarkSide-20k detector. One important example is the prediction of the accidental coincidence rate between S1-only and S2-only events. DEAP experience with TPB coating in a large detector is also put to good use. In addition, the Canadian collaboration is working on the development of Photon to Digital Converter technology, towards the next generation of detectors in the field on the ARGO timescale.

The Canadian contributions are outlined in Table 4.

4.3.3 Required resources

The DarkSide collaboration has submitted a request to CFI in the 2020 competition for a total of about $23M (of which $9M makes up the CFI portion). This would cover the three major necessary items – the acrylic vessel, the electronics and readout, and the underground argon facilities. These three items total roughly $5M each. There are a few other significant expenses such as the investigation of coatings, the SiPM development, and DEAP upgrades to make up the rest of the request.

In terms of personnel, the collaboration anticipates NSERC will continue the historic levels of funding for DEAP, about $800k/yr. The collaboration was successful obtaining NSERC funding in the 2020 round. Should the CFI proposal be successful, the collaboration anticipates the funding level for personnel will increase to levels in line with historic support.

The computing resources required for this collaboration are currently dominated by the DEAP experiment, comprising roughly 2PB of storage and 500 core-years per year, and growing at roughly 500TB per year. This is all covered by Compute Canada. With the move to DarkSide-20k, this is anticipated to grow to a maximum storage request of roughly 5PB and 1000 core-years per year. The computing requirements for ARGO are difficult to estimate but will continue the increase in storage and computing.

The DarkSide-20k group has also continued with the use of many Canadian resources. In particular, they rely on SNOLAB to provide low-background counting and expertise as well as a great deal of experience operating experiments underground. Engineering and technical support is supplied through the CPP++ MRS grant. Finally, TRIUMF is expected to support the electronics and DAQ system for DarkSide-20k and ARGO.

4.3.4 Outlook for the period 2027-2036

The path forward even on this time scale is clear for this group. Following the deployment and collection of data from DarkSide-20k, the majority of the effort will transition to the ARGO experiment. Prior to that experiment being situated, a group has been working on having underground storage of several hundred metric tons of argon to avoid cosmogenic activation.

4.4 DUNE

The Long-Baseline Neutrino Facility (LBNF) at Fermilab will produce the world's most intense neutrino beam, to be used by the Deep Underground Neutrino Experiment (DUNE), currently under construction and development. DUNE will consist of a far detector located at the Sanford Underground Research Facility (SURF) in South Dakota, at a distance of 1300 km from Fermilab, and a near detector to be located 575 m away from the neutrino source. The far detector will be modular and consists of four large rectangular liquid argon time-projection chambers (LArTPC), providing a total of >40 kilotons fiducial mass, allowing neutrino interactions to be reconstructed with unprecedented resolution. The near detector will consists of a modular setup of on-axis and off-axis detectors aimed at characterizing the intensity and energy of the neutrinos, which will be used as a reference for the far detector.

DUNE will be commissioned in stages with anticipated operations of the first LArTPC module in the mid 2020's. Two of the four modules will be commissioned with natural neutrino sources before the LBNF delivers its first beam, followed by third module commissioned one year after, and finally the fourth module three years after that. After about a decade of operations, the LBNF proton source beam intensity will be increased from 1.2 to 2.4 MW.

4.4.1 Research goals

DUNE enables a broad science program addressing some of the most fundamental questions in particle physics and cosmology. A comprehensive program of neutrino oscillation measurements using ν_μ and $\bar{\nu}_\mu$ will enable the determination of the neutrino mass hierarchy at the 5σ level after two years of running, regardless of the Charge-Parity (CP) violating phase value.

DUNE will also study solar neutrinos and be able to measure the ^{8}B and hep spectra which would provide further testing of the Standard Solar Model, characterize the matter-enhanced neutrino oscillations (MSW effect), and obtain further information about the neutrino floor needed by Dark Matter experiments.

Detection and measurement of the ν_e flux from core-collapse supernova would provide unique information about early stages of the core-collapse, unlike other neutrino detectors. Combined with gravitational waves and electromagnetic waves observations, as well as information from other neutrino experiments, would provide a comprehensive picture of the core-collapse event.

DUNE will also study atmospheric neutrinos to extract neutrino properties, such as the measurement of the mixing angle θ_{23} and obtain comparable sensitivities to the larger Hyper-Kamiokande detector.

Name	Institution	FTE for 2022-2027
Nikolina Ilic	IPP/Toronto	0.1 - 0.5
Claire David	York	0.5
Deborah Harris	York	0.5 - 0.8
Total FTE		1.0–1.8

Table 5: Canadian grant eligible investigators working on the DUNE experiment, with corresponding and projected research FTEs fractions.

4.4.2 The Canadian team and its impact

The DUNE collaboration consists of more than 1000 collaborators from over 190 institutions in over 30 countries. The Canadians collaborating on DUNE are listed in Table 5. The Canadian effort, currently firmly established at York University if focused around three key areas that are essential to the overall physics program.

- Near Detector: development of reconstruction algorithms for the Pixelated Liquid Argon TPC; a prototype detector has been commissioned at Bern and we will help commissioning and testing at Fermilab in an intense operating neutrino beam starting in 2021. These are essential for the precise predictions of the far detector spectra.
- Data Acquisition and Trigger Systems: the DUNE detectors will be producing 10 petabytes of data per year from various neutrino sources, calibration and mostly electronic noise. An efficient data acquisition system needs to be implemented for data reduction, filtering and storage. The data acquisition (DAQ) system will be based on the FELIX readout architecture which consists of FPGA-based electronic cards placed inside a commodity server. By working with the FELIX hardware, trigger algorithms will be developed and implemented, as well as trigger software development.
- Calibration and Computing: DUNE physics results will ultimately depend on accurate measurements of neutrino interactions within the LAr TPCs. A system made of ionizing laser periscopes is being developed; which will scan a good portion of the detector by generating straight ionization paths in the argon. The paths are reconstructed as curved projections, due to the in-homogeneous electric field which will allow to accurately reconstruct neutrino interaction events. Prototypes of periscopes will be installed at the CERN-base ProtoDUNE detector in late 2021. A DUNE computing model is also under development.

The Canadian team will also be contributing to various physics topics, which include improving the neutrino interaction model through auxiliary measurements made at MINERvA and T2K's Near Detectors suite; core-collapse supernova neutrinos and exotic physics.

4.4.3 Required resources

For the DAQ system, the needed infrastructure consists of 55 FELIX readout boards, and associated servers, and timing systems. Three of the boards will be used for local test stands to develop the hardware and software, while the remaining boards will be installed in the DUNE detector. The estimated cost of the needed infrastructure is $ 547 K, which has already been approved by Ilic's CFI JELF, and is pending approval from the Ontario Research Fund. Support will be requested from TRIUMF DAQ and electronics group as well as from MRS facilities at Alberta and Montreal.

For the calibration systems, David is in the process of requesting a CFI JELF to cover the costs for building and testing a prototype for a laser feedthrough system, namely the end-wall periscope.

The Near Detector Prototyping work will take place at Fermilab where Harris and David have joint appointments. It is likely that the primary equipment infrastructure for the prototyping task will be covered by other institutions. However the near detector will need a calibration strategy and it is expected that there will be hardware needs for that program that will develop over time and require funding.

For the computing needs, the model is under development and how challenges can be addressed. The overall global DUNE needs are 50 petabytes per year. The Canadian effort will focus on using GPU clusters to develop parallel algorithms as a contribution, and the needed resources will be requested from Compute Canada/NDRIO.

4.4.4 Outlook for the period 2027-2036

During that time horizon, LBNF is expected to be fully operational and will allow DUNE to reach and exploit its full physics potential and will be able to address one of its primary goal, namely CP violation. After a decade of running, and assuming the staged approach described earlier, a 5σ sensitivity to the Charge-Parity (CP) violating phase will be obtained for 50% of the values; providing insight into the origin of the matter-antimatter asymmetry. After 14 years of running, a 5σ sensitivity will be reached for 75% of CP-violating phases. Other components of the physics program, such as solar, atmospheric and supernova neutrinos will benefit from increased statistics and livetime. DUNE will also be sensitive to searches for Beyond Standard Model predictions, such as the existence of extra neutrinos and/or non-standard interactions.

4.5 HYPER-K

The Hyper-Kamiokande (Hyper-K) project was approved by the Japanese government in January 2020 and construction of the experiment began in Spring 2020. Hyper-K builds on the successes of the T2K and Super-K experiments with construction of an 8 times larger far detector and upgrades to the JPARC beam intensity to build a world-leading neutrino experiment. The detector design consists of a cylindrical tank (60m $\times$ 74m) filled with 260,000 tonnes of ultrapure water to form a water Cherenkov detector. Hyper-K will be commissioned in 2027 and will operate for 20 years. Canada has taken a leading role in Hyper-K since its conception.

4.5.1 Research goals

Hyper-K will study neutrino properties by making precision measurements of the distortion in the oscillation pattern, which is sensitive to sterile neutrinos and non-standard neutrino interactions. Coherent neutrino interactions in earth matter create an additional phase shift in the oscillation pattern, providing sensitivity to new non-standard interactions. Hyper-K is also a powerful astro-particle detector and play a role in multi-messenger astronomy, performing searches neutrinos from dark matter annihilation in the centre of the galaxy, sun, and the earth. Searches for other physics beyond the Standard Model, such as nucleon decays, magnetic monopoles, and Q-balls, are also possible.

Given the increased sensitivity of Hyper-K, systematic uncertainties will limit its measurements. The Canadian Hyper-K group leads the evaluation of systematic uncertainties and has taken the initiative to overcome this challenge by suppressing these systematics.

The neutrino flux still suffers significant uncertainties due to the hadronic interaction uncertainties in the neutrino production target. The Canadian group led the proposal for a new hadron production experiment, EMPHATIC, to systematically cover the phase space where current hadron interaction data are lacking. Canadians developed the NuPRISM concept, moving the near detector to different off-axis positions to sample different neutrino energy spectra.

The intermediate water Cherenkov detector (IWCD) of Hyper-K, which is led by TRIUMF, will study the neutrino differential cross section at the percent level. A workshop was organized in April 2019 at Victoria to explore machine learning by convolutional neural networks, resulting in the formation of an international group to study water Cherenkov detectors using machine learning (WatChMaL).

4.5.2 The Canadian team and its impact

The HK-Canada group, formed in 2018 with 12 faculty across Canada, is one of the larger Hyper-K groups and its contributions stand out with high visibility. Following the recent approval of the Hyper-K project in Japan, the group is expected to grow.

The Hyper-K-Canada group typically employs $\sim$ 4 undergraduate students.In September 2020, there are 8 graduate students, 6 MSc and 2 PhD, on the Hyper-K project.There are many projects for students to be involved and the number of graduate students is expected to grow.

Name	Institution	2022	2023	2024	2025	2026
Mauricio Barbi	Regina	0.55	0.55	0.55	0.7	0.7
Sampa Bhadra	York	0.2	0.2	0.2	0.2	0
Patrick de Perio	TRIUMF	0.8	0.8	0.8	0.8	0.8
Razvan Gornea	Carleton	0.3	0.3	0.3	0.3	0.3
Mark Hartz	TRIUMF/Victoria	0.6	0.6	0.6	0.75	0.75
Blair Jamieson	Winnipeg	0.6	0.6	0.6	1	1
Dean Karlen	TRIUMF/Victoria	0.7	0.7	0.7	0.7	0.7
Nikoley Kolev	Regina	0.7	0.7	0.7	0.7	0.7
Akira Konaka	TRIUMF/Victoria	0.7	0.7	0.7	0.85	0.85
Thomas Linder	TRIUMF/Winnipeg	0.45	0.45	0.45	0.5	0.5
John Martin	Toronto	0.5	0	0	0	0
Barry Pointon	BCIT	0.15	0.15	0.15	0.15	0.15
Total FTE		6.25	5.75	5.75	6.65	6.45

Table 6: Canadian investigators working on Hyper-K, with corresponding research FTEs

4.5.3 Required resources

The Canadian group submitted requests to NSERC RTI, 2020 CFI-IF, and planned submission to 2023 CFI-IF, of $16M, which is about 10% of the expected international contribution, consistent with the Canadian group size in the Hyper-K collaboration. In addition, the Canadian group has expressed interest in the continuing operation and upgrade of the OTR beam monitor and potential contribution for the remote handling system in the neutrino beam facility, whose plan is yet to be developed.

Additionally, a request for Tier-1 Hyper-K computing with 2-4 PB storage is planned for Compute-Canada. T2K currently uses about 700 TB of storage of data and simulations used in analyses on Compute Canada dCache space. 14 GPU-years have been allocated (out of 20 requested) for FY2020 and requested 50 for each of the following two years for our current RAP.

The mPMT design and prototyping is under way with support from TRIUMF and MRS facilities at Victoria, Winnipeg, Carleton, and Alberta. This will continue into the construction phase for IWCD and Hyper-K. Once the funding is approved, requests to the MRS facilities at Victoria, Winnipeg, and Carleton will be submitted to support the mPMT production. TRIUMF has made a significant remote handling contribution to the neutrino beamline for T2K, such as the remote maintenance of the most downstream beam monitor, and the design and construction of the manipulator system in the common service cell of the target station.

4.5.4 Outlook for the period 2027-2036

Hyper-K operation with accelerator neutrino beam is planned for 10 years from 2027 to 2036. Non-accelerator astroparticle physics study will continue an additional 10 years until 2046. Upgrades are under consideration to enhance the detector performance and physics capabilities and the choice of upgrades will be decided based on the breakthroughs observed during the broad range of the Hyper-K program. A second Hyper-K sized detector is being considered in Korea (T2HKK or KNO). Although the statistics is reduced by an order of magnitude, CP violation is enhanced by a factor of 3, providing a similar sensitivity as the Hyper-K detector. Introduction of Gd in Hyper-K is another potential upgrade that will enhance its neutron detection capability.

Although there is no concrete plan yet, realistic international contributions to the Hyper-K upgrade is expected to be a similar level as Hyper-K, or $150M. For T2HKK, Korea will become the host country and international partners would provide contributions. In this scenario, the scale of the Canadian contributions would be around $15M.

4.6 IceCube (and P-ONE)

The IPP Project IceCube Neutrino Observatory is currently the world's largest neutrino detector constructed to detect high energy neutrinos from cosmic rays and astrophysical sources. It is located near the South Pole Station, in

Name	Institution	FTE
Ken Clark	Queen's	0.20
Mattias Danninger	SFU	0.20 - 0.50
Carsten B. Krauss	Alberta	0.40
Roger W. Moore	Alberta	1.00
Nahee Park	Queen's	0.70
Juan Pablo Yanez	Alberta	0.50
Total FTE		3.0

Table 7: Canadian grant eligible investigators working on IceCube and P-ONE, with corresponding research FTEs.

Antarctica, instrumenting more than a cubic-kilometer of the deep ice with a 3D array of photo-detectors. IceCube, with its low-energy extension DeepCore, is sensitive to neutrinos from a few GeV to the EeV-scale.

A global effort is underway to expand the capabilities and sky coverage of neutrino telescopes and Canada is preparing to take on a major role with the proposed Pacific Ocean Neutrino Explorer (P-ONE) off the coast of Vancouver Island, BC.

4.6.1 Research goals

IceCube has demonstrated the potential of high energy neutrino detectors. At the lowest energies, IceCube's DeepCore opened a window to pursue precision neutrino measurements. The experiment observes atmospheric neutrinos at an unprecedented rate, down to energies of about 5 GeV, enabling measurements of neutrino oscillation parameters Δm^2_{32} and $\sin^2\theta_{23}$, and to search for other phenomena that would distort the atmospheric neutrino spectrum, such as non-unitarity of the neutrino mixing matrix, sterile neutrino states, and non-standard interactions. The measured atmospheric neutrino oscillation parameters are compatible with and comparable in precision to those of the dedicated experiments, such as MINOS, T2K, or Super-Kamiokande.

At the highest energies, IceCube established the existence of extraterrestrial, astrophysical neutrino flux. The recent multi-messenger observation triggered by a 290 TeV neutrino event detected by IceCube provided the first evidence of an astrophysical source of high-energy neutrinos, the blazar TXS 0506+056. Multi-messenger observations triggered by this IceCube detection provided new insights into the energetics and environment around the blazar's supermassive black hole.

IceCube continues to lead the indirect-detection search for spin-dependent dark matter, focusing on the Sun as the source, and has recently combined results with the leading spin-dependent direct detection experiment (PICO) to produce more model-independent limits.

P-ONE will be complementary to the capabilities of IceCube. Operating the telescope in water provides easy service access to the instruments. It also comes with unique advantages including the possible to change the detector geometry, e.g. cluster the detector for low energy physics then separate for high energy measurements and re-arrange the detector geometry to optimize energy sensitivity. Operation in water results also in better source identification due to a smaller point spread function.

4.6.2 The Canadian team and its impact

The Canadian IceCube program has established specific expertise in the study of neutrinos at energies up to the PeV-scale. This expertise has been leveraged to establish leadership in the international collaboration in the key analyses of the project, including: atmospheric neutrino oscillations, indirect dark matter searches, atmospheric neutrino fluxes, particle physics at the highest energy sources (including acceleration mechanisms), tests of long-baseline vacuum oscillation flavour ratios and of Lorentz invariance with high energy neutrinos, supernova neutrinos and beyond the standard model searches.

Currently the complete group includes six faculty across 3 institutes. The research FTEs of the team members is summarized in Table 7.

Canadians served as co-conveners for both the PINGU analysis group and the IceCube oscillations working group.

The long-term vision is to fully exploit the potential of IceCube in key physics topics, and build on Canadian expertise to deploy and operate P-ONE as part of a global network.

The IceCube groups in Canada have enjoyed extraordinary success in attracting excellent students and postdocs in the recent past. Over the past ten years, the Canadian group has trained a total of four postdoctoral fellows, eight graduate students (five PhD and three MSc) and more than 12 undergraduate researchers.

An extension to IceCube was approved by the U. S. NSF and European funding agencies in 2018 to add further instrumentation and calibration devices to the DeepCore region. Seven new strings, with closer spacing, assembled with new types of optical modules (Multi-PMT Digital Optical Module) will be deployed to improve the low-energy sensitivity, performance and angular acceptance compared to the original optical modules of IceCube. New strings for the IceCube Upgrade will include several new calibration devices to provide extensive calibration data to enhance the current understanding of photon propagation inside the ice. This will enhance the angular resolution of high-energy neutrino events, which is essential for the identification of high-energy neutrino sources. In addition to the calibration devices, there will be several prototype optical modules installed which have been designed for IceCube-Gen2, the next-generation high-energy neutrino telescope at the South Pole, instrumenting more than 10 cubic-kilometer of deep ice.

Canadians are playing an active role in the development of the new optical modules and are working on the embedded software readout of the new detectors, as well as leading IceCube's trigger and filter board which will oversee the development of new trigger algorithms using the new detectors.

The IceCube Upgrade work pursued by the Canadian group will have an extensive synergy with the work required to develop similar trigger and reconstruction algorithms for the P-ONE detector which will use almost identical optical modules used in the IceCube Upgrade. The Canadian group is also interested in R&D work for new, low background, and fast photodetectors such as digital SiPMs for the next generation of neutrino telescopes. This work will be performed in partnership with TRIUMF and Sherbrooke. The Canadian HyperK group is pursuing similar optical modules for HyperK.

The IceCube Upgrade lays the foundation for full-scale next generation facilities distributed around the world that aim for more than an order of magnitude increase in the sensitivity to high energy neutrinos. These next generation detectors, such as the IceCube-Gen2 facility or the newly proposed, Canadian-led P-ONE experiment will use IceCube Upgrade technology to provide a rich dataset of extremely high energy neutrino interactions for multimessenger astronomy, neutrino flavour physics and Beyond the Standard Model (BSM) physics searches. In the coming 5 year period, the Canadian group plans to maintain its position of leadership in several different areas of IceCube physics analysis, build on its established effort in calibration and triggering of the IceCube detector, and leverage these skills and detector knowledge for the design and construction of the P-ONE detector.

4.6.3 Required resources

The main focus for the development of equipment is on the planning, construction and operation of P-ONE. A multi-institutional CFI application led by the University of Alberta has been submitted in 2020 to provide the Canadian funding for the first ten-string module of P-ONE. Partner contributions from the US and Germany have already been secured for this phase of P-ONE.

The high energy neutrino community in Canada has been highly successful in securing computing resources though Compute Canada and CFI. The contributions had an out-sized impact in the discoveries of extragalactic neutrinos and later in the discovery of the TXS 0506+056 blazar as a neutrino source. The current computing allocation has remained largely stable for several years, and is projected to continue. There will be an increase in usage as the P-ONE project becomes more advanced. The University of Alberta also hosts a CFI-funded GPU batch system dedicated to IceCube with 144 GPU cards and 410 CPUs readily available for Canadian and international collaborators.

P-ONE will lean heavily on the electronics experts available in Canada as part of the MRS program. The electronics development for new P-ONE optical modules and upgraded IceCube modules will rely on MRS electronics personnel, such as the Alberta CPP+MRS. Due to the scale of P-ONE, TRIUMF is expected to also play a major role in the development of the P-ONE electronics systems. SNOLAB will support P-ONE through radioactivity measurements to make sure that the components of the optical modules of P-ONE will not induce large amounts of background.

4.6.4 Outlook for the period 2027-2036

During this period, the first stage of P-ONE will have already been deployed and will be collecting data. The IceCube-Gen2 upgrade will also be in full operation. For P-ONE, the focus of the Canadian group will be to operate the detector and to maximize the impact on the data analysis. For astroparticle physics, the vision for neutrino astronomy revolves around establishing a planetary observatory where P-ONE can play a crucial role. A global network of neutrino telescopes has been proposed under the name PLEνM (speak: plenum). P-ONE thrives to be an integral part in this new international network. The need for networking between the distributed neutrino telescopes becomes obvious when looking at the complimentary regions of optimal sensitivity for telescopes in the northern and southern hemisphere, showing only small areas of overlap.

Canadian's expect to take a lead in analyzing both P-ONE and IceCube data using high energy neutrinos to probe for physics beyond the Standard Model. With the deployment of multi cubic meter detectors in the pacific ocean several PeV events every year can be expected. For the IceCube Upgrade, the Canadian interest resides in studies of unitarity of the neutrino mixing matrix as well as the ordering of neutrino mass-hierarchy.

4.7 NA62

The NA62 experiment at CERN is designed to study rare kaon decays and measure decay branching fractions with high precision. It follows pioneering work done at BNL with the E787 and E949 experiments in measuring the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay mode. NA62 uses a decay-in-flight technique enabled by a low mass silicon pixel detector for tracking of the intense incident beam with a 1 GHz rate. The experiment also uses a liquid krypton calorimeter and a ring-imaging Cherenkov detectors for particle identification and energy measurements. The experiment relies critically on high resolution timing, kinematic measurements, particle identification, hermetic vetoing and redundancy of measurements. An initial run of NA62 was completed in 2015 followed by data-taking periods during 2016-2018. Future running of the experiment is planned for the 2021-2023 period.

4.7.1 Research goals

The decay process $K^+ \to \pi^+ \nu\bar{\nu}$ is highly suppressed in the Standard Model (SM) and precisely calculated at the 10^{-10} level. The measurement of this ultra rare decay process provides a unique opportunity to probe for new physics beyond the SM at very high mass scale ($\mathcal{O}(3000)$ TeV), and would complement direct searches conducted at the LHC. NA62 is aimed at measuring the decay of $K^+ \to \pi^+ \nu\bar{\nu}$ with a sensitivity of $\mathcal{O}(50)$ SM events.

NA62 has a rich physics program which includes also tests of lepton universality in other important kaon decay processes; as well as searches for lepton number and flavor violation, and heavy neutrinos in the few hundreds of MeV mass range. Exotic reactions are also explored to search for new weakly interacting particles and to probe a hidden sector. Rare radiative kaon decays will also be measured to study the interplay of electroweak and strong interactions at low energies interpreted with Chiral Perturbation theory.

The goals of NA62 are complementary to other Canadian particle physics projects searching for new physics at high mass scales as well as those investigating neutrino properties and hidden sectors.

4.7.2 The Canadian team and its impact

The Canadian group, in a collaboration of approximately 200 scientists, brings in its unique expertise from the BNL rare kaon decays experiments, and the PIENU experiment at TRIUMF which is studying lepton universality in the pion sector. The Canadian faculties collaborating on NA62 are listed in table 8, and are complemented by postdocs and students. The Canadian team is focusing on the analysis of the $K^+ \to \pi^+ \nu\bar{\nu}$ signal and backgrounds. To improve particle identification, in order to retain high efficiency for pions while rejecting muons, the Canadian group initiated a machine learning project in conjunction with TRIUMF's data science program which resulted in a factor of 5 improvement over existing multivariate techniques.

Canadian involvement in NA62 includes contributions to the calorimetry and tracking. The liquid krypton calorimeter is crucial to the NA62 rare decay program because it plays a key role in the photon veto and particle identification systems. The Canadian team provided a new device for monitoring the purity of the liquid krypton; a small time-projection chamber and data acquisition system built at TRIUMF was implemented in collaboration with

Name	Institution	FTE
Toshio Numao	TRIUMF	1.0
Douglas Bryman	TRIUMF/UBC	1.0
Total FTE		2

Table 8: Canadian grant eligible investigators working on NA62, with corresponding FTE fractions.

the CERN Cryogenics group. The Canadian team participated also in the operation and development of important components of the kaon tracking systems.

4.7.3 Required resources

Support for participation in the NA62 and other rare decay experiments e.g. PIENU, has been provided by NSERC. Levels of support required for future efforts (2022-2028) are estimated to be $250K/yr. No significant funds are expected to be requested for major hardware projects although TRIUMF support to be requested includes small technical contributions e.g. electronics components for selected projects including liquid Kr calorimetery monitoring and possible pixel system development. Computing is primarily done with CERN resources supplemented by Compute Canada systems consisting of 60 core-years and 150 TB of storage.

4.7.4 Outlook for the period 2027-2036

Currently, there are no plans to extend the Canadian involvement in the NA62 experiment beyond 2028.

4.8 PICO

The PICO collaboration aims to directly detect dark matter using the moderately superheated bubble chamber technique. The active liquid employed is a fluorine-rich target, C_3F_8, which allows PICO to investigate the spin-dependent channel due to the very high spin enhancement factor from the single unpaired proton in ^{19}F and its natural isotopic abundance of 100%. The low mass number also leads to a peak sensitivity in the low WIMP mass range of tens of GeV/c^2 and below, an area of much interest to dark matter experiments. In the spin dependent (proton) sector the superheated detector technology has published world-leading results for several years, with the most stringent limits set by the PICO collaboration.

4.8.1 Research goals

The primary goal of the PICO collaboration is the discovery of dark matter using a bubble chamber optimized for nuclear recoil detection. This will be pursued through a significant increase in the size of the detector from 40L to 330L with the PICO-500 experiment, and the technology can eventually be used to measure the solar neutrino flux using the CEνNS

PICO is the leading experiment dedicated to dark matter searches with a spin-dependent target. The Scintillating Bubble Chamber (SBC) collaboration is using many of PICOs ideas and techniques to explore the feasibility of using bubble chambers with liquid argon and xenon as active mass. We expect that ultimately the community will embrace the best way to reach the next goal, so we foresee a possibility that PICO will merge with SBC to build a large scale bubble chamber for the next generation of dark matter search.

4.8.2 The Canadian team and its impact

The Canadian groups on PICO have taken on the largest part of responsibilities for the design, construction, operation, and data analysis within the collaboration. Canadian PICO members have continued to innovate and improve the bubble chamber technology, leading the development and implementation of the novel cleaning protocol for low background bubble chamber components for PICO-60 and PICO-40L. The pressure and temperature control systems, optical read out, lighting trigger and data acquisition systems will again be Canadian led for the PICO-500 experiment. Canadians are also contributing to the assays using germanium counters at SNOLAB in order to keep track of the background budget of the experiment and aid in the careful selection of the materials.

Name	Institution	FTE
Ken Clark	Queen's	0.60
Jacques Farine	Laurentian	0.10
Guillaume Giroux	Queen's	0.50
Carsten B. Krauss	Alberta	0.50
Ian Lawson	SNOLAB/Laurentian	0.50
Caio Licciardi	Laurentian	0.20
Tony Noble	Queen's	0.75
Alan Robinson	Montréal	0.50
Marie-Cécile Piro	Alberta	0.50
Ubi Wichoski	Laurentian	0.40
Alex Wright	IPP/Queen's	0.05
Total FTE		4.6

Table 9: Canadian investigators working on PICO, with corresponding research FTEs

4.8.3 Required resources

PICO-500 is the largest low background chamber we know how to build and operate at this point. R&D efforts at a small scale have shown promising early results suggesting that alternate surface materials for the containment of the active liquid will be straightforward to establish. With a technical solution in hand, a mid-sized CFI-IF grant would enable PICO to construct a ton scale bubble chamber in a time frame of 5-8 years in the framework of an international effort.

PICO holds a Compute Canada allocation for the experimental data and processing. Increasing restrictions in accessibility and increased capacity in Canada allowed Canadian groups to take over the responsibility of primary computing provider. We expect that we will continue to be able to secure allocations with the new digital research infrastructure organization.

PICO has therefore been strongly relying on MRS and SNOLAB resources in the past, mostly for the completion of PICO-60 and crucial design aspects of the PICO-40L detectors. For PICO-500, MRS personnel will once again play a critical role in the design process for the inner detector. TRIUMF is involved in PICO through the appointment of K. Clark, but the lab has so far not found a significant role in PICO. SNOLAB as host institute has supported the PICO program significantly since its inception and has agreed formally to support the construction work for PICO-500 with significant investment to accommodate PICO requirements for the shielding tank among many other commitments the lab is taking on. SNOLAB also supports the positions of two research scientists working on PICO whose local expertise and dedication continue to be vitally important to make PICO experiments a success.

4.8.4 Outlook for the period 2027-2036

PICO is investigating alternate materials to contain larger volumes of active liquid, which will let the experiment grow in size and therefore sensitivity. This increase in sensitivity makes possible more than solely a dark matter search: it can be used as a flavour-insensitive way to detect neutrinos from supernovae and possibly observe Coherent Elastic Neutrino-Nucleus Scattering (CEνNS). This would allow a large future PICO-like detector to help constrain solar neutrino parameters. Using alternate target fluids, including hydrogen instead of freon would make available phase space with lower mass dark matter due to the kinematics of the interaction. Combined with the strong suppression of electron recoils, this could make PICO a significant player in the low mass dark matter field.

One of the long-term physics goals is also the merger with the SBC collaboration. In order to continue producing world-leading spin-dependent dark matter limits, PICO will require funding to construct the larger detector as described. This is expected to be supported by the Canadian system through CFI and NSERC, as it has for PICO-500. As with all SNOLAB-based experiments, the advancement of PICO will require a significant involvement and commitment from personnel at SNOLAB.

Initial molecular dynamic simulations have shown that there may be directional information in some acoustic channels which is not yet being exploited. The lure of a detector which is insensitive to electron recoils and also provides directional information means that PICO will be exploring the feasibility of the extraction of directional information in an existing test detector.

4.9 SNO+

SNO+, located at SNOLAB, builds on the success of the Sudbury Neutrino Observatory (SNO) experiment by replacing the heavy water in SNO with liquid scintillator, extending the range over which SNO+ probes neutrino physics down to $\sim$ 1 MeV or less while improving energy resolution. SNO+ liquid scintillator will be loaded with Tellurium to enable the search for neutrinoless double beta decay of the ^{130}Te isotope. With 780 tonnes of liquid scintillator target, SNO+ also has the capability to study the properties of neutrino oscillations with reactor and solar neutrinos, and to study the earth's radioactive heat budget with geoneutrinos. SNO+ will also be sensitive to neutrinos from a galactic core-collapse supernova.

4.9.1 Research Goals

Neutrino mass is arguably the only confirmed example of physics beyond the Standard Model. The nature of neutrino genereation is still unknown and neutrinos may have a Dirac mass, Majorana mass, or a mixture ob both. If neutrinos are Majorana fermions, neutrinoless double beta decay ($0\nu\beta\beta$) will take place in some nuclei. The measurement of this processes would show the Majorana nature of neutrinos and constrain models of neutrino mass generation.

The primary scientific goal for the SNO+ experiment is to develop an economical and scalable approach to search for $0\nu\beta\beta$ and to apply this approach to achieve world-leading sensitivity in the Majorana mass range corresponding to the inverted neutrino mass hierarchy for the light=neutrino exchange mechanism. SNO+ will search for $0\nu\beta\beta$ of Tellurium-130 (^{1}30Te) with 0.5% loading of Te in the detector at the initial phase, corresponding to 1.3 tonnes of ^{1}30Te. The experimental collaboration plans to increase the loading fraction of Te beyond 0.5% in order to increase the sensitivity to $0\nu\beta\beta$.

The physics goals of SNO+ extend beyond the $0\nu\beta\beta$ search to include measurements of geoneutrinos, reactor neutrinos, solar neutrinos and supernova neutrinos. SNO+ will measure the Δm^2_{21} neutrino mass splitting through the detection of reactor antineutrinos that have undergone oscillations with sufficient precision to resolve the current tension between measurements of Δm^2_{21} by KamLAND (reactor) and the global solar neutrino data. SNO+ is sensitive to solar neutrino interactions above 2.5 MeV (the $Q_{\beta\beta}$) of ^{1}30Te and will be able to pursue ^{8}B solar neutrino detection, allowing for the measurement of the solar neutrino up-turn. It is expected that SNO+ will detect hundreds of neutrinos in a variety of detection channels from a galactic core-collapse supernova. SNO+ will make time, energy and flavour resolved measurements. SNO+ also plans a pre-supernova alarm based on antineutrinos expected to be emitted during the silicon-burning phase immediately preceding the supernova and to participate in the SNEWS2 supernova neutrino detection network.

The $0\nu\beta\beta$ program of SNO+ is complementary to and in competition with other $0\nu\beta\beta$ programs including Xe-based EXO/nEXO and Ge-based MAJORANA/GERDA/LEGEND-1000. The SNO+ program is focused on the development of an economical method to scale the NLDBD isotope mass. SNO+ sensitivity to solar neutrinos complements the Hyper-K experiment, which also aims to measure the solar neutrino up-turn with a much larger detector mass, but significantly worse energy resolution and threshold. SNO+ sensitivity to supernova neutrinos complements the Hyper-K and HALO experiments.

SNO+ began operation in 2017 with a Water-Fill Phase, which lasted to 2019. In 2019, purification of liquid scintillator (LS) and filling with LS began until the COVID-19 pandemic necessitated the suspension of operations in April 2020. The LS phase will be followed with the Phase I double beta decay operation starting with 0.5% Te loading from 2022-2026. SNO+ is expected to reach a ^{1}30Te $0\nu\beta\beta$ half-life sensitivity of $> 2 \times 10^{26}$ years after 3-4 years of operation.

Name	Institution	FTE
Askel Hallin	Alberta	0.5
Carsten Krauss	Alberta	0.2
Juan Pablo Yanez Garza	Alberta	0.75
Doug Hallman	Laurentian	0.19
Christine Kraus	Laurentian	0.81
Clarence Virtue	Laurentian	0.28
March Chen	Queen's	1.0
Ryan Martin	Queen's	0.15
Art McDonald	Queen's	0.16
Alex Wright	IPP/Queen's	0.94
Aleksandra Bialek	SNOLAB/Laurentian	1.0
Erica Caden	SNOLAB/Laurentian	0.6
Bruce Cleveland	SNOLAB/Laurentian	0.22
Richard Ford	SNOLAB/Laurentian	0.13
Chris Jillings	SNOLAB/Laurentian	0.25
Szymon Manecki	SNOLAB/Laurentian	0.65
Rich Helmeer	TRIUMF	0.12
Total FTE		7.95

Table 10: Canadian investigators collaborating on SNO+ with approximate research FTEs dedicated to the project.

4.9.2 The Canadian team and its impact

Canadian groups lead the SNO+ experiment and are involved in all aspects of the hardware and data analysis. There are some physics topics and hardware responsibilities that Canadian groups have a strong focus on; there are no areas of SNO+ that have zero Canadian involvement. Among 50 faculty and research scientists collaborating on SNO+, 21 (listed in Table 10) are from Canada. The Canadian SNO+ collaboration contains 11 postdocs and RAs and 12 graduate students, with typical numbers of graduates students ranging up to 17.

Over the 2022-2026 period, the expected number of HQP to be approximately constant. Canadian HQP fill a number of leadership and technical roles within SNO+ including SNO+ Detector Manager, calibrations lead postdoc, Data Processing working group leader, Tellurium Chemistry/Chemical Engineering postdoc, Scintillator Quality Assurance co-lead (PhD student), and Supernova working group deputy (PhD student).

4.9.3 Required resources

The infrastructure for SNO+ is built and installed, and the 2022-2026 period will focus on data taking and the extraction of science. LS fill operations are led by and being completed by SNOLAB. Operating costs for completing the purification, synthesis and deployment of Te-loaded scintillator in SNO+ are supported by a combination of: CFI IOF funds, the SNO+ NSERC SAP Project grant, and also by significant contributions by SNOLAB.

The Compute Canada allocation for SNO+ (04/2020-03/2021) is 422 core-years Cedar and 2,000 TB of dCache storage (on the ndc-sfu system). In combination with SNO+ collaboration grid computing resources in the US and UK, this has been sufficient for Monte Carlo and data processing, and data storage. No increase in computing needs for SNO+ are anticipated at this time. SNO+ with partial-fill LS is already taking data at the planned for higher rates (of a scintillator detector compared with water Cherenkov).

Technical support activities and requirements for SNO+ are all based at SNOLAB. SNOLAB is leading the AV scintillator fill operation. SNOLAB resources will be required for assistance with tellurium process operations. Examples of SNOLAB resources that are a good fit to SNO+ experimental requirements are: transport logistics (surface-mine-underground for tellurium process reagents and waste), process system engineers and operators (originally hired by SNO+, now employed full-time by SNOLAB, experience process system engineers and operators have been running the SNO+ liquid scintillator purification plant and have the desired expertise to transition to assisting with tellurium plant operations).

4.9.4 Outlook for the period 2027-2036

Beyond SNO+ Phase I DBD (planned for 2022-2026) there are two options being considered: Phase II DBD with enhanced sensitivity or a pure LS solar neutrino run. After 1-2 years of the DBD Phase I operation with 0.5% Te loading, it will be know if background in the Te can be sufficiently controlled to the level where they are sub-dominant compared to external backgrounds and the ^{8}B solar neutrino background. If Te backgrounds are sub-dominant the Te loading in SNO+ will be increased from 0.5% to 1.5% followed by 2.5% (6.65 tonnes of ^{130}Te, giving sensitivity to $0\nu\beta\beta$ that scales almost linearly with the Te fraction. Recent R&D into Te loaded LS shows increased light yield that can compensate for the additional quenching when Te concentration is increased.

The alternative long-term program for SNO+ focuses on the measurement of pep, CNO and ^{7}Be solar neutrinos around 1 MeV with pure LS operation. This phase would involve the removal of Te from the LS down to the 1 ppm level and an effort to reduce the level of radon daughters ^{210}Pb, ^{210}Bi, and ^{210}Po.

4.10 SuperCDMS

SuperCDMS (Cryogenic Dark Matter Search) employs cryogenic semiconductor detectors, operated at a few tens of mK with the aim of detecting the weak and rare signal from WIMP interactions by measuring the ionization and phonon signal induced by the interaction. The next incarnation of the experiment will be located at SNOLAB. The initial payload will include ∼30 kg of Si and Ge detectors, surrounded by a massive shield against environmental radioactivity. The experiment is focusing on spin-independent dark matter with masses below about 10 GeV/c^2.

Construction of the setup at SNOLAB is underway and expected to be completed in 2021. Operation is then anticipated to start in 2022 and run for five years, covering the initial planning phase of this report. The initial payload will consist of 24 cryogenic detectors, 261 cm^3 each, arranged in four stacks (called towers) of six detectors each. To optimize sensitivities for different DM masses, we use two materials, silicon and germanium, and two sensor designs, iZIP (interleaved Z-sensitive Ionization and Phonon) which measures both phonons and charge independently, and HV (High Voltage) which only has a phonon readout but provides significantly improved energy resolution. Any ionization generated in these detectors is drifted across the detector by an applied bias voltage which produces additional phonons through the Neganov-Trofimov-Luke (NTL) effect. The ratio between the charge and primary phonon signals depends on the interaction type (nuclear vs. electron interactions), which is used for particle identification on an event-by-event basis in the iZIP detectors. HV detectors take advantage of a large NTL amplification for a low energy threshold at the cost of losing discrimination power on an event-by-event basis, though statistical discrimination is still possible.

4.10.1 Research goals

SuperCDMS aims to detect particle dark matter with masses below roughly 10 GeV/c^2, and to be one of the most sensitive technologies to search at masses near 1 GeV/c^2. This technology is then well suited to pursue three different areas of research:

1. The push in sensitivity for WIMP-like DM particles in the mass range from a few GeV/c^2 to a few hundred MeV/c^2, down to a level where the background is dominated by nuclear recoils from coherent scattering of solar neutrinos ("neutrino floor")
2. The push towards sensitivity to even lower energy nuclear recoils and thus to lower DM particle masses
3. The search for electron-interacting DM

All of these exploit the low-energy threshold afforded by the cryogenic technology.

The goal of superCDMS is to have 24 detectors of size 261 cm^3 each in four stacks. They will include two detector styles – the iZIP and the HV, the second of which provides improved energy resolution as described previously.

There is complementarity between the sCDMS efforts and those of several other projects. Expansion into lower DM mass ranges is the goal of several experiments. There is synergy among all the experiments in the field (dark matter as well as low-energy neutrino experiments such as SNO+ and EXO) with respect to material screening, cleaning, handling and the modelling and understanding of backgrounds.

4.10.2 The Canadian team and its impact

Canadian researchers are heavily involved with material screening and assay measurements at SNOLAB's low background counting facilities, as well as GEANT4 simulations for radioactive background characterization. The UdeM group focuses on measuring and developing models of radiation interactions in SuperCDMS detectors at previously unexplored ultra-low energy scales, using neutron elastic and Thomson scattering techniques. The Toronto group leads the collaboration's simulation effort and manages the collaboration's growing use of Compute Canada resources. As the host country, Canada will play an outsized role in on-site operations at SNOLAB. The entire Canadian team is fully engaged in all significant analysis efforts within the collaboration, with a focus on advanced statistical techniques for signal extraction, limit setting, and background rejection.

The Canadian group on SuperCDMS and CUTE is outlined in Table 4.10.2.

Name	**Institution**	**FTE**
Miriam Diamond	Toronto	0.9
Gilles Gerbier	Queen's	0.5
Jeter Hall	SNOLAB	0.75
Ziqing Hong	Toronto	0.8
Scott Oser	UBC	1.0
Wolfgang Rau	TRIUMF	1.0
Alan Robinson	Montréal	0.5
Silvia Scorza	SNOLAB	1.0
Pekka Sinervo	Toronto	0.2
Total FTE		6.65

Table 11: Canadian investigators working on SuperCDMS, with corresponding approximate research FTEs for 2020/2021.

4.10.3 Required resources

The SuperCDMS collaboration has secured funding from CFI in Canada, and DOE and NSF in the US. The support currently available is sufficient for both SuperCDMS and CUTE, totaling roughly $3-5M each. While the physical resources are well in hand, the personnel requirements may not have been met to this point. The collaboration is addressing this through growing the size of the group overall, notably with the addition of a new faculty member at the University of Toronto in 2020 (Hong).

In terms of computing resources, the majority of this is happening on the Compute Canada system, however the newly deployed "nearline" computing resources are SNOLAB are also being used. These represent 180 cores and 180TB of storage available for use by the collaborations.

4.10.4 Outlook for the period 2027-2036

As with all dark matter experiments, the SuperCDMS collaboration will be improving the detector sensitivity over the longer term. Unlike other experiments, these sensitivity improvements will be in three main directions.

The first long term gain aimed at by the SuperCDMS collaboration is to reduce the detector backgrounds in order to reach the neutrino floor for dark matter masses from a few hundred MeV to 6 GeV. This gain will be realized through the removal of cosmogenic backgrounds achieved by growing both the active crystals and the copper used surrounding the detectors. Steps are already underway to reduce the radon exposure of the detectors, which would be used in conjunction with the crystal growing facilities.

The SuperCDMS collaboration is also investigating improvements in sensitivity to nuclear recoils associated with dark matter masses of 10s of MeV. This requires a change in the detectors themselves, primarily the sensor readout and threshold. In association with this goal, sensitivity to electron recoils induced by dark matter with masses from $\tilde{1}$ eV to hundreds of keV will also be expanded through changes to the detector technology.

4.11 T2K

T2K is a long-baseline neutrino experiment that measures neutrino flavour mixing parameters by studying the transformation of muon neutrinos (and antineutrinos) produced by the J-PARC accelerator in Japan to other flavors at the Super-Kamiokande (SK) detector located 295 km away from J-PARC. The success of the experiment relies on a very intense neutrino beam, a massive water Cherenkov Detector, and the ability to make precise predictions of what oscillation signatures will look like at that far detector through a campaign of auxiliary measurements. Researchers from Canadian institutions have been leaders in establishing the in all of these areas in the past, and now with the high statistics that have been accumulated the current effort is on minimizing the systematic uncertainties.

4.11.1 Research goals

The experiment recently published in the journal Nature the first significant constraint on the CP- violating phase δ, a result which is having a profound impact on the community at large and the planning for the next generation of oscillation experiments. T2K has also made the most precise measurements of the mixing angle θ_{23} and neutrino mass squared splitting Δm_{23} using muon neutrino and antineutrino disappearance measurements. T2K expects to continue running through 2020-2024 with roughly equal neutrino- and antineutrino-mode running to further improve the sensitivity of this first indication of CP violation, and to improve the precision of its measurements of θ_{23} and Δm_{23}. The run plan after 2024 is still under discussion with management at J-PARC and requires striking a balance between the budgets for beamline operations and Hyper-Kamiokande (Hyper-K) construction. Given the timing of the Hyper-K construction, the 2022-2026 period for T2K represents one for transition overall for the experiment, and especially for T2K-Canada.

T2K plans to run with Gadolinium added to the far detector this year (SK-Gd) which will expand the physics reach by improving the detector's efficiency for detecting neutrons. T2K is also upgrading its near detector suite with two new detectors with improved acceptance for high angle charged particles and improved granularity in its solid scintillator near detectors. T2K-Canada is involved with the Gadolinium upgrade through its collaboration on SK but is not involved in the Near Detector upgrade. On the neutrino source side, there will be an accelerator shutdown in 2021 for J-PARC to upgrade the proton source so that the beam power in 2022 and beyond can reach more than twice what was achieved prior to the shutdown. The increased beam intensity requires upgrades to proton beam monitors and development of new monitors that can operate stably in the high intensity environment. T2K-Canada is involved in the proton beam monitoring through the construction, maintenance, and operation of the Optical Transition Radiation (OTR) Monitor, which measures the beam's transverse profile just before it hits the production target. T2K-Canada is also continuing to lead the simulation and analysis of the OTR data. Through Mark Hartz's joint appointment with Kavli IPMU, T2K-Canada is also involved in the development of a new non-destructive profile monitor, called the Beam-Induced Fluorescence (BIF) Monitor, that can operate at very high beam intensities. The BIF Monitor is under development under T2K-Canada leadership and is a promising new technology that will also contribute to improving the neutrino beam stability and flux prediction. The shutdown not only requires but also enables these upgrades because the 2021 shutdown is when the upgraded OTR Monitor and BIF monitor can be installed.

There are many avenues being pursued to improve the oscillation measurements already made by T2K thus far: one is simply accumulating more statistics with this improved proton source, but even more will be gained by running with improved detector sensitivity with Gadolinium (SK-Gd), and by investigating ways to make the most of the wealth of data accumulated thus far. T2K-Canada plans to play a role in the near detector analyses to improve the Far Detector predictions, and increasing the neutrino interaction channels that can be used, especially with SK-Gd. Finally, T2K it will provide important input in joint analyses with NOvA and atmospheric data from SK and IceCube/PINGU and will enhance the global sensitivity to the mass hierarchy.

During the 2022-2026 period many T2K Collaborators will be shifting their efforts to the next generation long baseline experiments DUNE and Hyper-Kamiokande, both of which have borrowed heavily (literally and figuratively) from the strategies and tools that have been developed by T2K.

4.11.2 The Canadian team and its impact

The period of this long range planning exercise is one of transition for the T2K experiment, as described above. Many members are ramping down on their T2K efforts and moving on to "next generation" efforts that were inspired by the success of the T2K experiment.

Name	Institution	2022-2023	2024	2025-2026
Mauricio Barbi	Regina	0.25	0.25	0
Sampa Bhadra	York	0.5	0	0
Deborah Harris	York	0.5	0.5	0.25
Mark Hartz	TRIUMF/Victoria	0.3	0.3	0.15
Blair Jamieson	Winnipeg	0.2	0	0
Akira Konaka	TRIUMF	0.3	0.3	0
Thomas Lindner	TRIUMF/Winnipeg	0.05	0.05	0.05
John Martin	IPP/Toronto	0.5	0	0
Total FTE		2.6	1.4	0.45

Table 12: Canadian investigators working on T2K, with corresponding approximate research FTEs

4.11.3 Required resources

4.11.4 Outlook for the period 2027-2036

The T2K project will have been subsumed by the DUNE and Hyper-Kamiokande experiments during this era, so we do not expect to request any support specifically for T2K during this period.

4.12 VERITAS

VERITAS (Very Energetic Radiation Imaging Telescope Array System) is a ground-based detector studying astrophysical gamma rays with energies in the Very High Energy (VHE) band - from approximately 80 GeV to over 30 TeV. The detector consists of four 12-m imaging atmospheric Cherenkov telescopes (IACTs) situated at the base camp of the Smithsonian Institution's Fred Lawrence Whipple Observatory on Mount Hopkins, near Tucson, Arizona. VERITAS is one of three large IACT arrays world-wide. The next-generation project, the Cherenkov Telescope Array (CTA) is still several years away.

4.12.1 Research goals

The VERITAS experiment has science goals which cover both astrophysics and particle physics, often in combination. The particular thrust for VERITAS is the investigation of gamma rays from astronomical sources, produced by charged particles accelerated to extreme energies. This makes these detectors very powerful and wide-ranging with a number of different specific effects which can be studied.

Perhaps the most significant physics covered by VERITAS in light of the recent discoveries by IceCube and other telescopes is the ability to shed light on the origin of high energy cosmic rays. While several methods of acceleration to very high energies have been proposed, there is no source currently understood. This may also tie into furthering the understanding of the physics of Active Galactic Nuclei (AGNs). While many of these have been identified by Fermi and ground-based detectors, the acceleration mechanism remains unknown.

VERITAS also has the capability of studying the annihilation of WIMPs, particularly those of higher mass. This would involve a search of galactic centres to identify the gamma rays from this process. This search is complementary with all of the direct detection experiments happening at SNOLAB, both current (DEAP-3600, DAMIC, PICO) and future (SuperCDMS, SBC, etc.)

The experiment is working through possible upgrades in the longer term, but there is no convergence yet.

4.12.2 The Canadian team and its impact

The original contributions of the Canadian group were the provision of the individual mirror facet mounting hardware (an adjustable, three-point gimbal system on each of the 1400 mirror facets) and the programmable digital delay modules necessary for the array trigger system. Canadian hardware contributions have continued apace through the delivery and operation of several custom calibration systems (for precision mirror alignment, LED flasher PMT calibration, and mirror reflectivity monitoring).

The Canadian group also has a long history of major contributions to software and physics analyses. On the software side, post-docs with the McGill group were responsible for both of the major analysis packages still used by the collaboration, and another post-doc was one of the first in the collaboration to use machine learning techniques (for a cosmic-ray electron spectrum measurement).

Institution	**Name**	**FTE**
Ken Ragan	McGill	1.0
David Hanna	McGill	0.5
Total FTE		1.5

Table 13: Canadian investigators working on VERITAS, with corresponding approximate research FTEs for 2020/2021.

4.12.3 Required resources

Given the potential dissolution of the Canadian group, no resources are currently anticipated for the upcoming period. The group is funded through 2023.

4.12.4 Outlook for the period 2028-2036

There are no plans for Canadian involvement in the post-2028 period.

5 Other Projects

5.1 Physics Motivation of Future Accelerators

Planning has begun for accelerator projects beyond that of the LHC. These include electron collider concepts: the ILC, FCC-ee, and CLIC, and proton collider concepts HE-LHC and FCC-hh. There is also exploration of electron hadron colliders including the LHeC and FCC-he, as well as a muon collider concept. In this subsection we will give a few highlights of some of the interesting discovery scenarios of these future accelerators, and subsequent subsections will discuss specific projects that Canadians are actively involved in.

The discovery of the Higgs boson is thus far the crowning achievement of the LHC physics program. All measurements of the Higgs are consistent with SM predictions, but as yet no measurement is more precise than 10%. More precise measurements may be able to uncover deviations and physics beyond the SM. Future colliders will be able to improve the precision on nearly all of the measurements done at the LHC; lepton colliders can exploit the clean environment and the significantly reduced background to increase precision. Lepton colliders can also exploit knowledge of the initial state to infer that a Higgs was produced and can thus have increased sensitivity to invisible or exotic decays of the Higgs (and of other heavy SM particles). High energy hadron colliders can use the significant increase of the production cross section of the Higgs to improve the measurements as well as potentially discovery heavier Higgs-like states. Electron hadron machines have some of the advantages of both and should have complementary sensitivity.

One aspect of the Higgs that is currently very poorly measured is the Higgs potential. The shape of the potential is the *cause* of electroweak symmetry breaking, but as yet there is no direct evidence that the wine bottle potential of the SM is what happens in nature. The derivatives of the Higgs potential at the minimum are probed by multi-Higgs production. It may be possible have some sensitivity to two Higgs production with the full run of the HL-LHC, but a higher energy hadron collider has a significantly higher cross section. With sufficiently high energy, three Higgs production may also be possible. Measurements of the potential can also reveal the cosmological history of the electroweak phase transition. In the SM, the early universe has electroweak symmetry restoration and a smooth transition to the low energy vacuum. If the potential is modified, then there could be a more violent phase transition, and this could solve the matter anti-matter asymmetry of the universe in models termed electroweak baryogengesis.

High energy colliders can directly produce and discover new heavy states. To get a rough sense of scale, a 100 TeV collider has the approximate discovery potential for coloured states with masses up to 10 TeV, electroweak states with masses up to 2 TeV, and resonant production up to 20 TeV, with the precise numbers being model dependant. This has implications for a broad class of models. For example, in models that solve the hierarchy problem such as supersymmetry, there is significantly more parameter space probed than the LHC. Furthermore, if no discovery is made, this would point to direct evidence of fine-tuning of the electroweak scale at one part in 10,000, a measure of the severity of the hierarchy problem.

Even without direct production of new states, any new accelerator can be sensitive to new physics at high scales. All heavy new physics can be parameterized via effective field theory (EFT), and sensitivity to EFT operators can be achieved either through high energy or high precision measurements. For example, at a high luminosity collider on the Z pole such as FCC-ee, if one could achieve a precision of 2×10^{-6} on the width of the Z, this would translate to sensitivity to a new physics scale of 50 TeV. At a hadron collider, the high energy tails of kinematic distributions are sensitive to new physics that is well above the direct kinematic reach of the collider.

Dark matter is one of the most outstanding questions in particle physics. While there is no direct evidence of the scale of dark matter physics, the WIMP miracle suggests that the weak scale may be a fruitful one to explore. The simplest WIMP model with a single electroweakly charged multiplet points to the scale of 1-3 TeV and is out of reach of the LHC. This could be probed by a high energy lepton or hadron collider. The space of dark matter models is extremely vast, but there is significant discovery potential for dark matter and associated phenomenology in a wide range of different models.

A muon collider could potentially be at much higher energy than an electron collider because of the large mass of the muon. A muon collider would have many of the advantages of an electron collider such as a clean environment and a known initial state, but could have significantly higher kinematic reach. It would also have a higher effective energy than a proton collider with the initial state being a fundamental particle rather than a composite with partons that only carry a fraction of its energy. Finally, solutions to the longstanding $(g-2)_\mu$ anomaly predict new states with significant couplings to muons that may only be accessible with a muon collider.

5.2 Chiral Belle: R&D for SuperKEKB Electron Beam Polarization Upgrade

Chiral Belle is the R&D project associated with a proposal to upgrade the SuperKEKB e^+e^- collider in Japan with polarized electron beams in the high energy ring. The collision data would be recorded by the Belle II detector, discussed in Section 4.2. This is included in the KEK Roadmap 2022-2026 and the Belle II/SuperKEKB e- polarization upgrade team is submitting a White Paper on this project for the 2021 U.S. Snowmass process. Conceptual designs for the polarized source, spin rotator and Compton polarimeter are being developed, with the Canadian team focused on the polarimeter and spin rotator, as well as physics exploitation with Belle II. A significant effort is on the accelerator R&D. This will be followed by a Technical Design with a goal to install the necessary hardware into the SuperKEKB accelerator in the planned long-shut down in 2026.

5.2.1 Research goals

The weak mixing angle, θ_W, is a fundamental parameter of the Standard Model (SM) and the international subatomic physics community considers precision neutral current measurements to be among the highest priority ways to search for evidence of physics beyond the SM. Whether at low energy scales accessible via atomic parity violation measurements at TRIUMF and labs in Europe, energies of around 100 MeV in the QWeak or Moller experiments at Jefferson Lab, new measurements in ATLAS and CMS at the Z-pole supplementing the measurements from the CERN Large Electron Positron Collider (LEP) and the Stanford Linear Collider (SLC), or in the future proposed experiments at the EIC, ILC, FCC-ee or CEPC, the international research community allocates substantial resources to this precision electroweak program because the deviation of any measurement of $\sin^2\theta_W$ from SM expectations of its running or universality properties would be a clear and compelling signature of new physics. Chiral Belle would use the large number of collisions from SuperKEKB to make high-precision measurements of the so-called "left-right" asymmetry A^f_{LR} (where f is a final state fermion). This will allow precision measurements of $\sin^2\theta_W$ at energy scales complementary to other measurements.

Name	University	FTE
Rick Baartman	TRIUMF	0.2
Wouter Deconinck	Manitoba	0.3
Michael Gericke	Manitoba	0.3
Christopher Hearty	IPP/UBC	0.1
Tobias Junginger	Victoria	0.15
Juliette Mammei	Manitoba	0.25
Thomas Planche	TRIUMF	0.1
Michael Roney	Victoria	0.65
Total FTE		2.0

Table 14: Canadian grant-eligible investigators working on Chiral Belle, with corresponding research FTE for 2020. The remainder of the research time of Roney and Hearty is on the Belle II project.

The asymmetry A^f_{LR} is induced by interference between the photon, γ, and the neutral massive weak boson, the Z. Other new particles at higher energy scales can also interfere with the γ and Z, resulting in small differences from the expected value of A^f_{LR} and $\sin^2\theta_W$. The precise measurements proposed for Chiral Belle give unique sensitivity to new physics at high-energy scales including heavier Z-bosons. The measurements could also be sensitive to the presence of "dark bosons" predicted by many models of possible dark sector extensions to the Standard Model which is the subject of extensive investigation by theorists.

In addition to this precision electroweak program, a polarized electron beam will enable a precision measurement of the τ electric dipole moment, g-2, improve the sensitivity of lepton flavour violating processes, such as $\tau \to \mu\gamma$, and open new probes of QCD.

5.2.2 The Canadian team and its impact

In 2019 the Belle II Collaboration created the Beam Polarization Upgrade R&D Working Group led by J.M.Roney from the University of Victoria. A team of Canadian researchers has joined the Chiral Belle effort, are applying for NSERC project funding for R&D focused on the beam dynamics studies associated with the spin rotator design (TRIUMF and Victoria) and the Compton polarimeter (Manitoba). Spin rotators are used to align the polarized electrons produced by the injection system at the collision point, and the Compton polarimeter is used to continuously monitor polarisation of the electron beam with high precision. The team of Canadian investigators applying for NSERC funding to support the Chiral Belle effort is summarized in Table 14.

This project provides excellent opportunities and scope for the training of students and postdocs in a number of skill sets. Former trainees of team members have been successful in obtaining coveted positions in academia and in high tech industry and it is fully expected that the HQP on this project will also benefit in that manner. The HQP will have developed the skills and training associated with accelerator and instrumentation design, optimizing for high precision under the constraints of a functioning high luminosity electron-positron collider. The students and postdocs will be expected to publish papers on the outcome of their studies. They will also report on their work orally both to collaborators on this upgrade project at dedicated workshops and the Belle II collaboration, as well as at various appropriate conferences. Students will develop a deep understanding of all aspects of the experimental environment of their projects and will be taking ownership of their contributions, with which they will be uniquely identified. This will be of great benefit for recognition and future job prospects. As the project moves to the Technical Design and Construction phases, additional HQP will be trained. It is expected that by 2026 this project will involve roughly 6 graduate students and 3 postdocs on the Compton polarimeter, spin rotator and beam dynamics projects, precision beam polarization measurement project using tau events in Belle II and preparations for physics exploitation.

5.2.3 Required resources

The total cost of upgrading SuperKEKB with a polarized electron beam is expected to be roughly $25M. The Canadian team plans to contribute roughly 30% to the capital costs of the project with contributions to the Compton polarimeter and spin rotator projects.

Computing needs for the machine beam dynamics studies are the largest component of this R&D effort. The actual demands are still to be determined, but are expected to be roughly 10% of the Canadian Belle II computing needs.

Beam dynamics studies with spin tracking and spin rotator designs will call on TRIUMF expertise in accelerator physics. Detector design for the Compton polarimeter will call on resources from TRIUMF and detector MRS resources.

5.2.4 Outlook for the period 2027-2036

Once SuperKEKB has been upgraded with polarized electron beams, the goal is to ultimately collect 40 ab^{-1} of polarized data in order to extract the physics with Belle II, as outlined above. The plan is to complete the upgrades by 2027 and collect the data until the early 2030's. Analysis of that data is expected to be completed by 2036.

It is expected that future upgrades to Belle II may occur during this period to address machine background issues, but at this time the Canadian team is not expected to contribute to those efforts. The focus will be on operating the Compton polarimeter and extracting the physics enabled by polarization.

The electron-ion collider (EIC) is expected to begin in that period and we anticipate exploiting synergies related to polarization of the electron beam in the EIC project. The relationships with international partners will continue through the Belle II collaboration during this period.

5.3 HALO

HALO is a dedicated supernova neutrino detector that began full operation at SNOLAB in May 2012. The detector consists of 80 tonnes of lead instrumented with about 360 m of ^{3}He neutron counters shielded by 30 cm of water. Neutrinos from a supernova with energies of tens of MeV can excite nuclear states that emit one or two neutrons, leading to a sustained burst of detected neutrons. The concept of a lead-based supernova detector originate in Canada. As a heavy nucleus, lead has a greatly enhanced cross-section for the charged-current scattering of electron neutrinos, leading to enhanced sensitivity to this process in a way complementary to other detectors employing water and argon. HALO employs the ^{3}He neutron detectors from the SNO NCD phase and lead from a decommissioned cosmic ray station in Deep River, leading to a detector with very modest capital requirements. HALO is part the international SuperNova Early Warning System (SNEWS), an international network of neutrino detectors, designed to send alerts to astronomers.

HALO-1kT is a proposed supernova neutrino detector that would be sited at the Laboratorio Nazionale del Gran Sasso (LNGS). It is a detector of opportunity being pursued because of the availability of 1000 tonnes of Pb from the decommissioning of the OPERA experiment. In essence it would be a scaled up and optimized version of HALO that would achieve a neutron capture efficiency of 50–55% with 1.3 g of ^{3}He per tonne of Pb versus the 28% efficiency of HALO with 2.3 g of ^{3}He per tonne of Pb. With a larger target mass and a higher efficiency, HALO-1kT would have a 22-fold increase in event statistics over HALO at SNOLAB for a given galactic SN. A Letter of Intent has been submitted to the Scientific Committee of LNGS and a Scientific Proposal is in preparation for submission later this year.

5.3.1 Research goals

Supernova neutrinos span several areas of neutrino investigations, including Neutrino Messengers, Neutrino Properties, Dark Matter, and Astroparticle Physics Technology. The fit to the category of Neutrino Messengers is self-evident with an increasing number of terrestrial neutrino detectors capable of, and ready to, detect neutrinos from the next galactic supernova (NGSN) and the prospect of the measurement of the Diffuse Supernova Neutrino Background on the time frame of the next 20 years. The richness of the supernova neutrino signal drives, in part, the interest in capturing the data from the NGSN. The physics of neutrinos, as well as the astrophysics of core-collapse supernovae (ccSNe) and their central compact objects (CCOs), are strongly imprinted on the flux of supernova neutrinos, so the detection of neutrinos from the NGSN holds the promise of revealing Neutrino Properties; garnering insight into astrophysical aspects of ccSNe and their CCOs; and testing our ability to simulate the extreme physics involved in supernovae. With the recent observation of coherent elastic neutrino-nucleus scattering (CEνNS1) there is tremendous interest in the supernova neutrino detection capabilities of future large-scale Dark Matter detectors.

Name	Institution	FTE
Mauricio Barbi	Regina	0.30
Erica Caden	SNOLAB/Laurentian	0.1
Alan Chen	McMaster	0.05
Jacques Farine	Laurentian	0.05
Nicolay Kolev	Regina	0.20
Christine Kraus	Laurentian	0.13
Barry Pointon	BCIT	0.20
Clarence Virtue	Laurentian	0.75
Stan Yen	TRIUMF	1.0
Total FTE		2.78

Table 15: Canadian investigators working on HALO and HALO-1kT, with corresponding research FTEs.

5.3.2 The Canadian team and its impact

Canadians are leaders in the HALO project, constituting roughly half of the collaboration. They are likewise leading the upgrade discussions and the collaboration building process, with positive indications from the US and Italy.

The R&D for HALO-1kT is funded by NSERC and the CFI contribution to the Neutron Detector Characterization Facility has already been mentioned along with the enabling contributions from Laurentian, LNGS and the University of Washington. The project is Canadian-led and relies on significant contributions from LNGS (1000 tonnes of Pb) and the US DOE (10,000 liter.atmospheres of He-3). All indications are that Canadian contributions can leverage these international contributions and lead to the construction and operation of a unique SN neutrino detector.

In Canada, the current HALO program has supported one postdoc, 4 MSc students, and 9 undergraduates. The project has had the benefit of attracting many international collaborators to SNOLAB, including 5 US and 3 German undergraduates and an MSc student from France on a six month internship. A much larger contingent contributes to the experiment off-site. These students benefited from the comprehensive experience with a smaller experiment that can be more challenging to obtain within much larger collaborations. An upgraded detector at LNGS may train 2–3 times as many HQP.

5.3.3 Required resources

HALO at SNOLAB has drawn on technical support primarily from SNOLAB, TRIUMF, University of Washington, University of North Carolina, and Duke University. For the upgraded HALO detector at LNGS, additional technical support may be requested from some or all of these sources. Support will also be sought from the Groupe Technologique at l'Université de Montréal, and Carleton, Queens, and Alberta MRS resources. We expect significant engineering support from LNGS for an approved HALO at LNGS project. The most demanding technical challenge is the identification of appropriate neutron detection technology for such a large detector. Current candidates include boron or lithium-loaded scintillating fibers. A CFI request will be made to secure a Canadian contribution to the project. The computing needs for the upgraded HALO detector are still being estimated, but data rates and volumes will be rather modest.

The Canadian Astroparticle physics community can remain active in the supernova field by making a modest, approximately $5M, investment in HALO-1kT.

5.3.4 Outlook for the period 2027-2036

If approved, HALO-1kT can be operational for this full time period.

Name	Institution	FTE
Alain Bellerive	Carleton	0.10
Francois Corriveau	McGill	0.20
Total FTE		0.30

Table 16: Canadian investigators working on ILD R&D, with corresponding research FTEs.

5.4 ILC and ILD

The ILC is a proposed electron-positron collider that will operate initially at a centre-of-mass energy around 250 GeV to enable precision measurement of the Higgs boson. Exploring the precise properties of the Higgs boson is considered one the best windows to physics beyond the Standard Model at the TeV scale. The machine is also being designed to be upgradable to higher collision center-of-mass energies enabling precision studies of the top quark, measurement of the top Yukawa coupling and the Higgs boson self-coupling. The International Large Detector (ILD) collaboration is one of two approved ILC detector concept groups working toward the final design and construction of the ILC experiments.

While the ILC is the most advanced and mature proposal on the world-stage for an immediate deployment of a ”Higgs Factory” there are complementary electron-positron machines at the horizon: the Compact Linear Collider (CLIC) at CERN (collision energies of 380 GeV, 1.5 TeV and 3 TeV), the Circular Electron Positron Collider (CepC) in China, and the post HL-LHC Future Circular Collider (FCC-ee), both designed as Higgs factories but with at least an order of magnitude higher luminosity compared to the ILC. Both CEPC and FCC-ee could eventually be transformed into a higher energy hadron machine (collision energy of 100-150 TeV).

Muon colliders can in principle reach the highest lepton collision energies and the unique potential of a multi-TeV muon collider has been recognized by the international community to invest into R&D concept to demonstrate its technical feasibility.

5.4.1 Research goals

The physics motivation for a Higgs Factory sharpened with the discovery of the Higgs boson at the LHC in 2012. The prime focus of the ILC physics program will be the high-precision and model-independent measurements of the Higgs boson properties and precision tests of the Standard Model. The ILC can achieve percent level or better precision on most Higgs boson decay channels. It reaches sub-percent level sensitivity to invisible Higgs decays, searches for exotic Higgs decays and provides excellent sensitivity to decay modes that are challenging at the LHC (e.g. Higgs decay to charm). At a center-of-mass energy of 500 GeV, the ILC can also enable precision studies of the top quark, measurement of the top Yukawa coupling and the Higgs self-coupling.

To meet the stringent spatial resolution requirements dictated by the ILC physics programme, the ILD proposes a TPC as the central tracking detector. The single hit transverse spatial resolution goal of 100 μm represents an order of magnitude improvement over the conventional proportional wire/cathode pad TPC performance and approaches the fundamental limit imposed by diffusion. Achieving an optimal energy and mass resolution of all components of the final state will also be crucial. For this, a detector concept based on particle flow algorithms requiring very high-grained calorimeters has been adopted. Canadians are involved in the R&D associated to these two key aspects of the ILD.

5.4.2 The Canadian team and its impact

As shown in Table 16, a total of two Canadian faculty currently maintain a stake in detector R&D work for ILD/ILC. The teams are involved in both the Time Projection Chamber (TPC) and the calorimeters of ILD. Both teams were engaged in software/simulation and hardware efforts. The TPC work is guided under the LCTPC collaboration, while the calorimetry R&D is encompass by the CALICE collaboration.

Canada have been at the forefront of research for the development of novel gaseous detectors with members at Carleton, U de Montréal and UVIC. Both Gas Electron Multiplier (GEM) and Micro Pattern Gas Detector (MPGD) readout system have been developed for the ILD TPC and successfully tested with cosmic rays and in test beams.

The MPGD work has been also embedded in the CERN RD51 collaboration.

CALICE was originally formed to prepare the calorimetry for the ILC. It has since then expanded its scope to generic calorimetry with high granularity and precise timing to maximize the benefits of Particle Flow algorithms. The groups is also involved in the Analogue Hadronic Calorimeter (AHCAL) activities, one of the main axis of research of CALICE. Canada's dedicated analysis of the time information newly available with the AHCAL prototype. Each of the small cells is not only measuring energy deposition, it is also tagged with a time information at better than 1ns precision to further increase the needed tracking power of ILD over large volumes.

Both LCTPC and CALICE collaborations have technologies ready for final design. Over the past ten years, the ILD project has trained 15 undergraduate students and ten graduate students (MSc and PhD).

Canadian leadership within the ILD is also evident with several positions within the TPC and Calorimetry community being held by Canadians (e.g. LCTPC coordinator, Chair of the LCTPC speaker bureau, LCTPC technical board, CALICE Steering Board member, and subgroup convernership roles). A. Bellerive continues to be one of the LCTPC co-spokesperson, while he also represents Canada on the American Linear Collider Committee (ALCC).

ILC hardware and software projects are very well suited for undergraduate students and MSc theses. In the past decade, more than a dozen undergraduates, eight MSc level students and one PhD student have been trained.

Twenty-five signatories from eleven Canadian institutions supported the ILC Technical Design Report in 2013. Over the past year, interest in the ILC within the governments of Japan and the U.S. has grown considerably. The international community sees an opportunity for the ILC to be constructed for operation in the mid-2030's. The International Committee for Future Accelerators (ICFA) approved the formation of the International Linear Collider (ILC) International Development Team as the first step towards the preparatory phase of the ILC project, with a mandate to make preparations for the ILC Pre-Lab in Japan.

Overall detector designs have been developed by the global ILC community. The ILD and ILC construction is planned from 2026-2034 with R&D in 2021-2025. The ILD concept provides an opportunity for R&D in Canada which posses relevant detector expertise in calorimetry and gaseous detectors mentioned above but also in the area of radiation-hard silicon tracking detectors through previous collider experiments and RD50 at CERN. The currently proposed schedule for the ILC is: 2020-2021 Development plans for the ILC Pre-Lab, 2022-2025/6 ILC Pre-Lab, and 2026 ILC Accelerator and Detector constructions start.

It is noteworthy that the start of ILC detector construction coincides with the completion of the Phase-2 ATLAS upgrades which could make significant construction capabilities available.

5.4.3 Required resources

Significant funding and/or technical resources requests in support of a sizable Canadian participation in the ILC program is clearly directly dependent on the approval and derived final construction timeline of the ILC. An approved plan for a timely realisation of the ILC in Japan would be a catalyst to engage larger Canadian community to collaborate.

It is expected to take about 9-10 years to complete the ILC and its detectors. The deployment of the ILC detector will required a dedicated work-force of technical people with skills and abilities required to design and construct the complex apparatus which will rely on dedicated MRS/TRIUMF support.

It is expected that the computing, CPU and storage needs of the next electron-positron collider will be similar to the needs of an LHC experiment. This effort will need to be coordinate with New Digital Research Infrastructure Organization (NDRIO) within the national structure of digital research infrastructure ecosystem.

5.4.4 Outlook for the period 2027-2036

In case the ILC will be approved and realized, this period would initially be dominated by completing the construction of the ILC detectors and their commissioning. Towards the mid 2030's, the effort would predominantly shift towards physics analyses using the first ILC datasets.

5.5 LEGEND-1000

The LEGEND experimental program was established as a successor to the MAJORANA DEMONSTRATOR and GERDA projects to search for the neutrinoless double-beta decay ($0\nu\beta\beta$) of 76-Ge using isotopically-enriched High Purity Germanium (HPGe) detectors. The LEGEND-1000 detector, currently in preliminary design, will be the next step in the LEGEND experimental program and will deploy isotopic masses of the order of 1000kg. The LEGEND-1000 experiment would start operating in a phased approach (as more enriched Ge is produced), with initial commissioning targeted for 2026, and full operation (with all material present) near 2030, and of order 10 years of data-taking, with decommissioning in the late 2030s.

5.5.1 Research goals

The development of the experiment is imbricated in the U.S. down-select process for next generation $0\nu\beta\beta$ experiments. Based on the science case, it would be logical for LEGEND-1000 to be constructed at SNOLAB, and that is the baseline plan that is used by the collaboration to model expected backgrounds. There is thus a good opportunity for strong Canadian involvement in the LEGEND program, as this would become one of the (if not the) leading next generation experiment in $0\nu\beta\beta$ searches. The LEGEND-1000 experiment will target the inverted hierarchy region of parameter space, with a planned half-life sensitivity of the order of 10^{28} years. Advances in HPGe detector technology, such as the point contact geometry (PC), have been the direct result of R&D efforts in support of $0\nu\beta\beta$ searches with germanium detectors. These PC detectors have also been used in dark matter searches, and searches for coherent neutrino nucleus scattering. There is thus interest from a large community in improving this technology and developing a better understanding of charge propagation and signal formation in these devices so that they may be optimized. Half-life limits with sensitivities close to 10^{26} years have been demonstrated with HPGe detectors using relatively small target masses ($\sim$ 30 kg).

5.5.2 The Canadian team and its impact

Currently, only one group at Queen's University is involved in the LEGEND collaboration. The PI at Queen's has extensive experience in developing and characterizing p-type point contact (PPC) detector systems in the context of the MAJORANA collaboration, as well as developing software for analysis, data acquisition, and simulation. The group is currently "ramping up" participation in the LEGEND experiment with the hiring of a postdoc in March 2020. The group at Queen's is currently focused on developing capabilities to characterize PPC detectors as well as to better understand how large these devices can be made (less readout electronics if each detector is larger). If LEGEND-1000 is sited at SNOLAB, there will be a need to characterize a large number (500+) of PPC detectors, and the group at Queen's would be in a natural position to establish a large scale characterization facility. The group at Queen's is also generally involved in developing analysis and simulation software, including applications of machine learning to process PPC detector data. Of particular interest to Canadian groups are R&D work on:

- HPGe detector R&D (optimizing PPC, ICPC designs, etc.)
- Construction and operation of a detector characterization facility at SNOLAB
- R&D with LAr, using LAr depleted in 39-Ar, developing instrumentation, purification techniques and facilities, light propagation studies and optimization
- Developing novel readout electronics, e.g ASICs, in low background formats
- Developing low background mounts and cabling using novel materials
- Developing radioactive assaying capacity

Relationships with international partners including relative size of Canadian team within the collaboration. The Queen's group has two graduate students working on HPGe detectors and one PDF. The group is focused on developing the local laboratory and capability at the moment and is ramping up participation in the detector characterization working group for LEGEND.

Name	Institution	FTE
Ryan Martin	Queen's	0.5

Table 17: Canadian investigators working on LEGEND-1000, with corresponding research FTEs

5.5.3 Required resources

If LEGEND-1000 proceeds at SNOLAB, and there is a desire for Canadian scientists to contribute significantly, then it will be important for additional groups to join the project, at the level of 3-4 faculty, 6-10 graduate students and 3 PDFs. Those groups would naturally funding SAP-Project funding from NSERC to support HQP, at a level around \$300k/year. In addition, for Canadian contributions to be significant, the groups would need to coordinate and identify one or more subsystems to develop for LEGEND-1000, and CFI would be a natural partner to support that infrastructure. For example, the infrastructure to characterize detectors, or to purify LAr could both be significant contributions from Canada. If LEGEND-1000 is sited at SNOLAB, then the experiment will require access to storage infrastructure as a minimum and start to develop software tools around 2025. SNOLAB engineering support will be required in order to develop the design of the LEGEND- 1000 experiment as well as make use of SNOLAB's assaying capabilities. Canadian groups developing electronics for the experiment would benefit from expertise at TRIUMF and our MRS facilities. There would also be a large demand for mechanical and cryogenic engineering expertise to build the experiment. Relationships with other projects being conducted by Canadian subatomic physicists – either physics or technical.

Currently, no other Canadian groups are involved in LEGEND. However, there is significant experience in Canada that would benefit LEGEND, in particular related to LAr systems, readout electronics, and assaying. There are many synergies between the R&D tasks in LEGEND and other groups in Canada (see broader impacts section).

5.5.4 Outlook for the period 2027-2036

The LEGEND-1000 experiment should begin a phased operation around 2026, with "modules" of 250kg of detectors coming online every $\sim$ 18 months, so that the full experiment would be built by $\sim$ 2030 and operated for $\sim$ 10 years to probe the inverted mass hierarchy region of phase space, with a half-life sensitivity on the order of 10^{28} years. The costs and specific projects are too dependent on the future involvement of the Canadian community to discuss meaningfully.

5.6 MATHUSLA

The MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles) experiment is a dedicated large volume detector proposal on the surface above the CMS experiment at the Large Hadron Collider (LHC) to explore the lifetime frontier at the High-Luminosity LHC. The MATHUSLA collaboration presented a Letter of Intent to the LHC Council (LHCC), and operated a test stand on the surface above ATLAS in 2018. The next step towards CERN approval of the experiment is the submission of a Technical Design Report scheduled for early 2021.

5.6.1 Research goals

Although dedicated searches for new long-lived particles (LLPs) are actively performed by the LHC experiments ATLAS and CMS, detector size, trigger and background limitations severely curtail the range of LLP lifetimes, decay modes and masses to which they are sensitive. Particularly challenging are LLPs with very long lifetimes that decay dominantly outside of the ATLAS and CMS detectors. MATHUSLA could search for neutral long-lived particles (LLPs) without trigger limitations and with very low or zero backgrounds, allowing it to probe LLP cross sections and lifetimes up to several orders of magnitude beyond the reach of ATLAS and CMS.

MATHUSLA will consist of an air-filled decay volume, monitored by a robust multi-layer tracking system of plastic scintillators above and below. Decays of LLPs originating from collisions in CMS will be reconstructed as displaced vertices (DVs) of upwards traveling charged particles. MATHUSLA's position on CERN-owned land near CMS, separated from the IP by $\propto$ 100m of rock, will shield it from most collision backgrounds. For sufficient

Name	Institution	FTE (present)	FTE (future)
D. Curtin	Toronto	0.3	0.2
M. Diamond	Toronto	0.2	0.5
S. Robertson	Alberta	0.1	0.5
Total FTE		0.6	1.2

Table 18: Canadian investigators working on MATHUSLA, with corresponding research FTEs.

geometric acceptance of LLPs, the detector must be very large, with linear dimensions ∼100m and a height of ∼20m. MATHUSLA will be integrated into the CMS trigger system, enabling CMS detector activity to be associated to MATHUSLA LLP candidate events. This opens the prospect of determining both the LLP production mode and the decay mode, and even possibly the LLP mass range and spin. MATHUSLA will be able to resolve DVs from LLPs with masses $\propto$ 1 GeV all the way up to the weak or TeV scale, and with lifetimes approaching the cosmological upper limit of $\propto$ 1 s.

MATHUSLA can also act as an effective cosmic ray (CR) telescope for measuring extensive air showers (since an integral driver of the detector design is the identification of downward- going CRs as a background to LLP searches). The large detector area gives it good efficiency for primary CRs in the range $\propto 10^{14} < \mathrm{E} < 10^{18}$ eV.

5.6.2 The Canadian team and its impact

The Canadian core group comprises three grant eligible investigators, listed in table 18 while several additional Canadian theorists (including D. McKeen, D. Morrissey and D. Stolarski) were instrumental in developing the physics case and sensitivity studies, and are co-authors of the MATHUSLA experiment proposal. As such, Canadians provide key contributions to the experiment through phenomenology calculations and preliminary detector simulations that have informed the basic design of MATHUSLA, together with Canadian and international collaborators. The group will continue to provide input, such as updated reach estimates and increasingly precise background calculations, as the details of the detector parameters are determined. The group will also assist with interpretation of early data from the demonstrator.

The main technical challenge of MATHUSLA is to build tracking layers much larger than in any other existing particle detector, capable of reliably reconstructing displaced vertices and distinguishing upward-going from downward-going tracks, with the minimum possible production and operation cost. The layers will be composed of extruded plastic scintillator bars. Resistive Plate Chamber (RPC) layers are also being considered as a possible technology to enhance tracking performance. Scintillation light will be collected in a wavelength-shifting fiber (WLSF) embedded in the bar, and detected by a silicon photo- multiplier (SiPM) at either end. The bar will provide two orthogonal spatial coordinates (by width segmentation and time difference between ends) of the hit; accurate reconstruction of particle hit positions will require the relative timing from bar ends to be measured very precisely. In the immediate future, the Canadian team plans to construct and assess prototype mini-units to test various options for the scintillator bar geometry, fiber and SiPM models, timing electronics, and data acquisition systems. This work is already in progress, and funding requests are in preparation to support this effort.

The intermediate term goal for Canada is to participate in the construction and commissioning of the Demonstrator unit, as well as analysis of Demonstrator data. Once the technical design of the experiment has been established, it is anticipated that the Canadian group will contribute to the construction and commissioning of the full MATHUSLA detector in proportion to the size of the Canadian participation in MATHUSLA. Canadian experimentalists currently represent $\propto$ 10% of the overall MATHUSLA experimental effort, and the overall Canadian contribution (i.e. including theorists) represents a similar fraction of the proto-collaboration as a whole.

To date, the Canadian group has trained a total of two graduate and three undergraduate students on research topics related to MATHUSLA phenomenology and detector geometry.

5.6.3 Required resources

A modest funding request will occur for the Demonstrator detector hardware on a timescale of 2022 - 2023, followed by a CFI request in support of the construction of the full detector approximately mid-decade, depending on the

CERN approval status of the project. The anticipated size of the construction contribution is expected to be proportionate to the Canadian participation in the project.

The MATHUSLA datasets are expected to be relatively small compared to typical collider experiments, and similar in scale to a medium-size dark matter direct detection experiment. A ballpark estimate of data storage requirements can be obtained from the expected cosmic ray rate in the detector, ~ 2 MHz, which yields $\sim 6 \times 10^{13}$ events per year. The fraction of these events whose detailed properties will be stored, and the stored event size, are yet to be determined, but storage on the order of 100 TB/yr can be anticipated. The computing model has yet to be determined and the resource needs are expected to be modest.

5.6.4 Outlook for the period 2027-2036

The primary objectives of the MATHUSLA during this period will be detector operations and data analysis. From a Canadian perspective, the main resource need is anticipated to be for postdocs and graduate students. These group members may be based either at CERN or at their home institution depending on their specific involvement in ongoing operational activities. If detector upgrades are foreseen for this period, then it is likely that Canadian group members will also participate in the associated R&D. In this case it can be anticipated that there would be a need for modest RTI funding and also some access to MRS-supported resources.

5.7 MoEDAL

The MoEDAL (Monopole and Exotics Detector At the LHC) (MoEDAL) experiment is a dedicated detector array designed to detect magnetic monopoles and other highly ionizing massive particles. MoEDAL shares the same intersection region as the LHCb experiment at the Large Hadron Collider (LHC). During LHC Run-2 the MoEDAL experiment took 6 fb^{-1} of data at a centre-of-mass energy (E_{cm}) of 13 TeV. MoEDAL has placed world leading limits in the search for magnetic monopoles.

The MoEDAL Collaboration plans to deploy two new sub-detectors to its existing detector to expand the search for highly ionizing particles to searches for feebly ionizing and long lived particles during LHC Run-3 and beyond.

5.7.1 Research goals

The MoEDAL baseline detector is designed to detect Highly Ionizing Particle (HIP) signatures of new physics such as magnetic monopoles, dyons, Q-balls and massive (pseudo-)stable charged particles hypothesized in a number of physics scenarios beyond the Standard Model.

To detect these particles, the MoEDAL experiment uses Nuclear Track Detectors (NTDs), which suffer characteristic damage due to highly ionizing particles. The experiment is comprised of an array of plastic NTDs deployed around the (Point-8) intersection region of the LHCb detector. Monopoles would rip through the MOEDAL detector, breaking long-chain molecules in the plastic nuclear-track detectors and creating a minute trail of damage through all sheets. A clear indication of the path of a monopole would be an aligned set of holes with the trajectory pointing back to the collision point. MoEDAL also includes the magnetic monopole and massive charged particle trapping sub-detector (MMT). Its sensitive volume consists of 800kg of aluminium trapping bars deployed around the MoEDAL for study in the laboratory. Al bars are chosen due to its anomalously large nuclear magnetic moment. The exposed bars are monitored for the presence of monopoles using the ETH SQUID (Superconducting Quantum Interference Device) magnetometer. MoEDAL's passive detector technology allows it to operate without gas, electrical power, readout or trigger.

MoEDAL has placed the world's best limits on the search for Drell-Yan (DY) production of monopoles - where magnetic charge is explicitly detected - for magnetic charges (gD) up to 5gD. The experiment has also placed the most stringent limits on monopole production via photon-fusion, and for the first-time placed limits on spin-1 monopole production and DY production of the dyon.

In order to continue to push the search for highly ionizing avatars of new physics with the existing MoEDAL detector to higher center-of-mass energy (14 TeV) and significantly higher luminosity the MoEDAL Collaboration has requested to take data as part of the LHC's Run-3 program, starting in 2021. This extension of data taking was approved by the LHCC in 2020 and will also allow the group to continue the search for HIPs with much

Name	Institution	FTE
Marc de Montigny	Alberta	0.25
Marina Frank	Concordia	0.2
Claude Leroy	Montréal	0.1
Pierre-Philippe Ouimet	Regina	1.0
James Pinfold	Alberta	0.4
Gordon Semenoff	UBC	0.25
Jack Tuszinski	Alberta	0.1
Total FTE		2.3

Table 19: Canadian investigators working on MoEDAL, with corresponding research FTEs.

higher luminosity (30fb^{-1}) and to deploy two new planned sub-detectors MAPP (the MoEDAL Apparatus for Penetrating Particles) and MALL (the MoEDAL Apparatus for extremely Long Lived charged particles). This will allow the project to expand the physics reach of the MoEDAL experiment to include the search for fractionally charged/milli-charged/feebly ionizing particles with charges as small as $0.001e$ realized through detector elements called MAPP-mQP. Searches for extremely Long-Lived particles with lifetimes that can reach the order of 10 years will be realized through detector elements called MAPP-LLP. MAPP and MALL will be placed in the UGC1 gallery in the vicinity of the LHC interaction point. The size of the gallery is such that it is always possible to have a 6-10 m decay zone in front of the detectors. The intervening rock (30m) serves to shield the detector from Standard Model backgrounds.

5.7.2 The Canadian team and its impact

Canada had major responsibility in the design, construction and installation of MoEDAL. The MoEDAL NTD and MMT detectors are cycled in and out of the cavern by the Canadian group. The current MoEDAL spokesperson and the Technical coordinator are Canadian.

Currently, MoEDAL employs one Canadian postdoc, based at INFN Bologna, and eleven graduate students, of which five students - 4 PhDs and 1 MSc - are working in the MoEDAL-Canada group.

The Canadian groups are also responsible for the redeployment of the MoEDAL detector for Run-3 of the LHC and also the design, construction and installation of the Phase-1 (2021) MAPP detector. The MAPP detector is comprised two arrays of 100 (10 cm $\times$ 10 cm $\times$ 100 cm) high light yield scintillator bars, where each bar is readout by two low noise PMTs. These two sections are sandwiched between three ToF hodoscopes. Thus, a milli-charged particle would see 200 cm of plastic scintillator readout by four low noise PMTs, in coincidence. The whole device is protected by a hermetic veto system. The funding to complete this detector was provided by a category 2 SAP NSERC-RTI grant. The Canadian group is also responsible for the design of the Phase-2 (2022) and Phase-3 (2025) MoEDAL-MAPP detectors with an additional responsibility for their construction and installation. The Canadian group is responsible for the DAQ and analysis software of the MoEDAL-MAPP experiment as well as the DAQ software for the MAPP and MALL detectors. The machine learning software required for the analysis of the NTD detectors is provided by collaborators.

In terms of faculty members, the overall MoEDAL-Canada group consists of seven faculty members which represents about 9% of the MoEDAL Collaboration. The five theorists within the MoEDAL-Canada group are all members of the MoEDAL theory board.

5.7.3 Required resources

The MoEDAL requirement for equipment and infrastructure can be divided into three phases. Phase-1 for the MoEDAL-baseline detector (in operation since 2015) and the MAPP-mQP detector are already fully funded. MAPP-mQP is scheduled to be installed in 2021. Phase-2 will require partial funding from NSERC to realize the MAPP-LLP extension. During Phase-II the MALL detector is expected to be installed around 2022. During Phase-III, the project plans to install a size enhanced MAPP-2 detector around 2025. Beyond this, no additional funding request is foreseen for the the MoEDAL-MAPP detectors.

Technical support from NSERC SAP MRS program is currently utilized for an electronics technician at the 20%, level, which is expected to continue. No need of technical facilities or infrastructure at TRIUMF or SNOLAB is foreseen. However, the project will make use of the scintillator production facilities at FERMILAB.

The MoEDAL-MAPP detector will utilize a software trigger which requires storage of large amounts of data storage on the order of a few petabytes. The storage cost will be shared among the collaboration. The storage will be acquired over the lifetime of the experiment. About 500 TB are required at the start of detector operation in 2022. To service the MoEDAL-MAPP detector for Phase-III (installation in 2025, running in 2027) access to around 40 high performance (12-core, 256 GB RAM) compute-nodes is required to handle the computing needs (starting with about 10 compute nodes in 2021).

5.7.4 Outlook for the period 2027-2036

This period is covered by the HL-LHC and a second phase upgrade to MAPP (MAPP-2), an extended Long-Lived particle detector, is planned to be deployed at the beginning of this period. During the HL-LHC phase, data taking is expected with the full MoEDAL-MAPP-2 and MALL detectors. The physics reach of MAPP-2 in the search for the decays of a heavy right-handed neutrino is competitive with other experiments such ass CODEX-b, PHASER-2 and MATHUSLA. MoEDAL provides a vital complementarity to LHCb and MATHUSLA via a critical and unique sensitivity to intermediate to long lifetimes.

Beyond 2028 the vision includes working out the design and prototype of a dedicated experiment at a future collider, e.g. the planned 100 TeV FCC machine at CERN. There are additional plans for deploying initial elements of the “Cosmic-MoEDAL” experiment. This experiment consists of a giant array (10K m^2) of NTD detector deployed at high altitude. A Canadian was a co-leader on a 400 m^2 prototype Cosmic-MoEDAL experiment called SLIM that took data on Mt Chacaltaya in Bolivia between 2004 and 2010. The purpose of this experiment is to carry the search for the magnetic monopole from the TeV scale to the GUT scale.

5.8 Moller

Within the Standard Model, the combined Electro-Weak interaction strength of electrons is parameterized by the so-called electron Weak charge, which is itself related to the weak mixing angle, a fundamental parameter of the Standard Model that sets the degree of mixing between the Electromagnetic and Weak interactions [S. Weinberg, Reviews of Modern Physics, 46, 255–277 (1974)]. The MOLLER experiment [The MOLLER collaboration, arXiv:1411.4088 [nucl-ex]] aims to make the world’s most precise off-resonance measurement of the weak mixing angle, using polarized electron-electron scattering at Jefferson Laboratory. The experiment will test the interaction of electrons with respect to a number of new physics models and will search for electron substructure at the 10×10^{-21} meter (zeptometer) scale. The electron-electron interaction is the cleanest process that exists among fundamental particles, uncontaminated by nuclear interactions and experimentally extremely well controlled, and therefore a prime candidate to search for signatures of new physics

The SoLID experiment (short-baseline neutrino experiment in Belgium) and the P2 experiment at Mainz also propose to make measurements of $\sin^2\theta_W$ in complementary ways. The combination of these experiments will provide a clearer picture of the running of the weak mixing-angle with energy scale μ.

Generally, any of the other efforts in Fundamental Symmetries are complementary to MOLLER, but this is particularly true for the TRIUMF Francium experiment, which also plans to make a measurement of the weak mixing angle, and the proposed EIC and SuperKEKb polarimetry upgrade projects, which have electroweak motivations, including weak mixing angle measurements. The MOLLER project is complementary to similar measurements of the weak mixing angle at the LHC, because the LHC measurements are made on-resonance and sensitive to different new physics scenarios

5.8.1 Research goals

The goal of MOLLER is to determine the value of the weak mixing angle to very high precision as a sensitive test for physics beyond the Standard Model, including possible electron structure. To achieve this objective, the experiment must measure the parity-violating asymmetry (A_{PV}) in the number of elastically scattered, polarized electrons, from unpolarized electrons in a liquid hydrogen target to unprecedented precision. The asymmetry can be written down

Name	Institution	FTE
A. Aleksandrs	Memorial	0.2
S. Barkanova	Memorial	0.2
W. Doconinck	Manitoba	0.4
M. Gericke	Manitoba	0.7
J. Mammei	Manitoba	0.7
R. Mammei	Winnipeg	0.1
J. Martin	Winnipeg	0.1
E. Korkmaz	UNBC	0.3
W. van Oers	Manitoba	0.4
Total FTE		3.1

Table 20: Canadian grant eligible investigators working on Moller with corresponding FTEs.

using just basic physics principles and the Standard Model theory, parameterized in terms of the Fermi constant G_F , the fine structure constant α, and electron weak charge Q_W^e . The measured asymmetry is given by

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = meE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q_W^e \tag{1}$$

where $\sigma_{R(L)}$ are the scattering cross-sections for right(left)-handed helicity beam electrons. The electron weak charge is given by $Q_W^e = -1 + 4\sin^2\theta_W$, where θ_W is the weak mixing angle. The electron mass, m, G_F , and α are determined experimentally to extremely high precision by other experiments [M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)], while the asymmetry, the beam properties (stability, average polarization, and energy E), as well as the center of mass scattering angle (θ) will be measured using the MOLLER experiment. The measurement will be performed using the 11 GeV electron beam at Jefferson Laboratory and requires a large, highly efficient, and precise array of electron detectors.

The goal is to measure the asymmetry to an overall accuracy of 2.4%. The Standard Model prediction for A_{PV}, for the proposed experimental design, is $\approx 33 \times 10^{-9}$ and the 2.4% relative error goal corresponds to an overall precision of 0.7 ppb on the asymmetry measurement. The anticipated relative error on Q_W^e is also 2.4%. A 2.4% asymmetry measurement corresponds to a $\sim 0.1\%$ determination of the weak mixing angle.

5.8.2 The Canadian team and its impact

MOLLER is an international effort, presently involving more than 120 collaborators from the USA and Canada (the lead countries), as well as Germany, Italy, France, and Mexico. The current Canadian group (including faculty, postdocs, and students) includes about 20 people, which makes it the second strongest contiguous group in the project, behind Jefferson Lab. The FTE of faculty on the project are summarized in Table 20. On the Canadian side, MOLLER is in its 3rd NSERC funding cycle and on the US side the experiment has received first DOE funding for the 2020 budget, which makes it a firmly established project.

Since the last LRP, the Canadian team has made significant progress in leading the design of the magnetic spectrometer and the integrating detectors and associated electronics, and has established leadership roles in simulation and analysis software. For the integrating detectors, prototype development has been ongoing since 2013 for the detector modules and since 2015 for the associated electronics. Since 2013, there have been 8 detector prototype beam tests at the MAMI facility in Mainz, and at SLAC.

The group presently has 8 graduate students and 2 research associates working on the project, as well as a varying number of undergraduates. The team seeks to increase their graduate student contingent to about 16 students (roughly two per Co-PI) and maintain that level until the end of the experiment. The team also expects to increase the number of postdoc positions for the duration of the experiment, especially during the commissioning and data production period. MOLLER Canada anticipates training around 40 HQP during the course of the project.

5.8.3 Required resources

Equipment and Infrastructure Needs A CFI IF proposal was submitted for the 2020 competition, to request funding to contribute the integrating detector array and electronics, with a total CFI budget of $6M (including other contributions). HVMAP pixel detector R&D was funded a few years ago through an NSERC RTI. The MOLLER Canada group anticipates requesting funding of the electron tracking detectors needed for MOLLER beam polarimetry through an NSERC RTI category I application in 2021 parallel to the CFI funding. In the event that the CFI application is not successful, the MOLLER Canada team are planning to apply for NSERC RTI, category III funding in 2021, for a scaled down detector contribution to the MOLLER experiment.

Technical Support Needs The CFI project is currently going through the full TRIUMF GATE review process and has passed the GATE 1 review, which provides TRIUMF approval to submit the CFI with TRIUMF support and requires the detailed technical design, resource loaded schedule and budget. The personnel requirements for the final electronics development, as specified by the GATE 1 review committee, amount to a total of 2.3 FTE of engineering at TRIUMF, over a 3 year period, currently projected to start in 2020.

Dedicated personnel for detector and electronics development is also available through the DOE MOLLER budget that was recently approved by the US government for the 2020 fiscal year. The assembly and testing of the detector array modules will take about 3 years and encompasses many technical tasks, including mechanical and electronic assembly, machining of parts that goes beyond the manufacturing process carried out at companies, quality assurance of the large number of components, as well as installation related tasks at Jefferson Laboratory.

Computing Requirements The Canadian group has a 173 core-years allocation on Compute Canada for the current cycle, that is being used for simulations and analysis. The group anticipates that their computing needs will increase to around 400 core years by 2025 and maintained there until the end of the analysis effort around 2033. The MOLLER experiment expects to collect about 2 to 4 PB of data that are planned to be mirrorede in Canada.

5.8.4 Outlook for the period 2027-2036

The years from 2027 onward will consist of production data taking until the desired statistical precision is achieved. The minimum time required for this is 3 years. Assuming the float in the DOE schedule is needed to complete construction and commissioning, this data production would begin in 2027 and proceed through at least 2030. This will probably be followed by a year or two of analysis, followed by publication of the main result and ancillary measurements perhaps in 2032. We consider this the long time-scale scenario. If the construction is completed by the early mark in the DOE schedule (2025), then everything shifts to be completed two years earlier.

5.9 NEWS-G

The NEWS-G collaboration searches for low-mass WIMPs using spherical proportional counters (SPCs) filled with light atomic mass gases0, such as neon, methane, and helium. The collaboration was created in 2014 by Queen's University Canada Excellence Research Chair (CERC) Gilles Gerbier. SEDINE, the first implementation of a SPC to search for dark matter by the NEWS-G collaboration, was built in 2015 at the Laboratoire Souterrain de Modane (LSM), in France. At the time of publication (2017), the results obtained with the SEDINE detector were the world's most sensitive for very low mass dark matter particles. NEWS-G has now embarked on the next phase of the experiment, a larger SPC made from very-low-activity copper, that will be installed in a compact radiation shield at SNOLAB by the end of 2020.

The evidence that supports the existence of non-baryonic cold dark matter in the universe is overwhelming. Weakly interacting massive particles (WIMPs) are a class of dark matter candidates that are emerging from beyond-the-Standard-Model theories. For example, supersymmetric extensions to the Standard Model give rise to a thermally produced WIMP with a mass typically ranging from 10 GeV/c^2 to 10 TeV/c^2. Direct detection experiments are searching for the signal of the coherent elastic scattering of the Milky Way halo WIMPs with the detector's target nuclei. These searches are notoriously challenging in part due to the small interaction cross-sections, leading to expected rates that are orders of magnitudes smaller than the ones from natural radioactive backgrounds. Experiments using large liquid xenon time projection chambers (TPCs) are currently leading the direct search for SUSY WIMPs, but the signal remains elusive. This, in addition to the lack of evidence for SUSY at the Large Hadron Collider (LHC), warrants the extension of the search to low mass WIMPs. The exploration for low-mass, sub-GeV WIMPs, is further motivated by the predictions of several recent theoretical frameworks, such as dark sector, asymmetric dark matter, and generalized effective theory. Direct detection experiments aiming at the detection of light WIMPs require both extremely low thresholds to detect nuclear recoils with sub-keV energy, as well as light atomic mass targets to optimize momentum transfers.

5.9.1 Research goals

The NEWS-G detector consists of a metallic spherical shell, held at ground potential. A small sensor is placed at the center of the sphere at the end of a grounded metallic rod and is held at positive high voltage. The resulting electric field is mostly radial, except near the sensor rod which disturbs the field, and falls as $1/r^2$. The interaction of a particle with the target gas creates the primary ionization, which is then drifted towards the center of the sphere along the electric field lines. As the electrons approach within approximately 1 mm of the sensor, the magnitude of the electric field becomes sufficient for the production of secondary ionization. The signal is generated by the ions drifting away from the sensor. The low capacitance of the sensor, which allows for low electronic noise, in combination with the large amplification of the signal, allows for single electron detection and therefore makes the SPC a powerful detector for low energy nuclear recoils. Background events from track-like energy deposits and from radioactive contaminants at the inner surface of the SPC can be discriminated based on the rise-time of the pulse, which is correlated to the spatial extent of the energy deposition and to the longitudinal diffusion of the primary ionization which increases for longer drift times.

The NEWS-G collaboration reported in 2017 on the first dark matter search results with a SPC at the Laboratoire Souterrain de Modane (LSM). At the time of publication, the results set new constraints on the spin-independent WIMP-nucleon scattering cross-section for WIMP masses under 0.6 GeV/c2.

The next phase of the NEWS-G experiment is a 140-cm ultra-low background (C10100 copper) SPC that is currently being installed at SNOLAB. A novel sensor called ACHINOS has been developed by NEWS-G collaborators from the Aristotle University of Thessaloniki (Greece) and at CEA-IRFU (France). The ACHINOS sensor greatly improves the performance of large sized detectors by increasing the magnitude of the electric field at large radii. The SPC will be placed in a concentric low-radioactivity lead shield, with the innermost 3 cm of lead made from ultra-low 210Pb content archaeological lead. The interspace will be continuously flushed with pure nitrogen to mitigate the presence of radon. The detector will then be surrounded by 40-cm of high-density polyethylene to shield against neutrons from the environment.

The construction of the 140-cm diameter SPC that will be installed at SNOLAB Sudbury (Canada) was completed earlier this year. The two C10100 hemispheres were fabricated in France. An electroplating method developed at PNNL (USA) was implemented to add 0.5 mm of pure copper to the inside of the hemispheres, in order to limit the impact of the 210Pb contamination found in the C10100 copper used to fabricate the SPC. This work was performed underground at LSM to limit the production of cosmogenic radioactive backgrounds. The hemispheres were then welded into a sphere using an electron-beam in France. After cleaning and etching the sphere underground at LSM, the sphere was kept isolated from the radon naturally present in the air. While the polyethylene shield components are being fabricated at the University of Alberta, a complete fitting of the SPC in the lead shielding was achieved at LSM during the summer of 2019. A temporary neutron shielding was constructed to allow the full commissioning of the NEWS-G SPC in low background conditions at LSM, and a physics run has been conducted in October 2019 using pure methane gas. The data analysis efforts to search for dark matter recoils on protons are underway. On October 15th, 2019, the SPC and its shield at LSM were decommissioned and shipped to SNOLAB. The full commissioning of NEWS-G at SNOLAB was expected to to take place at the end of spring 2020, but the novel Coronavirus pandemic put all the activities on hold. With the re-opening underway, there is hope to reach this milestone before the end of the year.

The WIMP Mass Frontier For a given detector exposure and background levels, there are two factors determining the ability to search for lower WIMP masses: the detection threshold and the atomic mass of the target nucleus. In SPCs, the low threshold is guaranteed with single electron detection and limited by the ionization energy of the target nucleus. Further improvement on the minimum threshold attainable is at reach thanks to the use of gas mixtures engineered for a lowered W-value (e.g. Penning effect). Low atomic mass nuclei allow for optimal momentum transfer from the scattering of low-mass WIMPs. SPC operation with neon/CH4 mixtures, pure CH4 and helium/CH4 mixtures has been demonstrated. Operation with pure molecular hydrogen gas is in principle feasible, but represents a safety challenge due to the high flammability of hydrogen. Operation with helium mixture is also challenging due to the low drift velocity of electrons at low electric fields. This issue can be addressed with enhanced control on the gas purity, and with the stronger electric field provided by the ACHINOS sensor. Several experiments with low thresholds are seeing an unexpected increase in background at very low energy which could associated with single ionization events. In the NEWS-G detector, the low drift velocity of the primary ionization allows for 2 the discrimination of single electron events from multiple electron events. This allows for dramatic background discrimination by setting an effective threshold to events that have at least two electrons. Currently, the ionization yield of the recoils of the various target nuclei is poorly studied at very low energy. The NEWS-G collaboration is conducting a nuclear recoil ionization yield measurement campaign that will allow for the characterization of the SPC with different gases near threshold that will allow for a better understanding of the detector's response to very low mass WIMPs.

The Background Frontier The main background in NEWS-G is expected to come from the ^{210}Pb contamination of the copper in the bulk of the 1.4-metre SPC, more specifically from the bremsstrahlung photons from the beta-decay (end-point 1.2 MeV) of its daughter, ^{210}Bi. Notoriously difficult to measure with conventional high purity germanium counters (minimum sensitivity ¿100 mBq/kg), the XMASS Collaboration has recently measured the ^{210}Pb content of commercial OFC using a XIA alpha counter at 17 - 40 mBq/kg. Samples of C10100 copper of the NEWS-G sphere were measured with this method and show contamination of 28.5 mBq/kg. Monte-Carlo simulations indicate that this contamination will correspond to a background of 1.5 events/kg/day/keVee, 5-times more than all other backgrounds combined. This event rate is reached after two years of cooling (decay of the short lived cosmogenic isotopes) of the experiment underground, the time needed for background from cosmogenic activation of the copper to become negligible. For this reason, the NEWS-G collaboration is planning the installation a new high-pressure 60-cm SPC made from ultra-low radioactivity copper to replace the 1.4-metre SPC after the experiment becomes background limited. This next-generation SPC will be fabricated out of 6N copper (purity greater than or equal to 99.9999%) from the Mitsubishi Material Corporation (MMC, Japan). This is the highest purity copper available on the market. The XMASS measurement of MMC 6N copper reaches the instrument sensitivity, giving only an upper limit for the 210Pb contamination at ¡ 4.1 mBq/kg. Taking this upper limit as the pessimistic case, this would correspond to a factor 4 improvement on the sensitivity to WIMPs between 0.3 and 1.0 GeV/c2. The ultimate control on copper backgrounds will be achieved only from the electroforming of a complete spherical shell at SNOLAB. Experience at the Pacific Northwest National Laboratory (PNNL) has shown that electroforming leads to the purest copper as of today. Electroforming in the deep underground environment at SNOLAB will also allow for control on the cosmogenic activation of copper. The replacement of the C10100 140-cm SPC in the NEWS-G shield at SNOLAB, first with a 6N SPC, and then with an electroformed copper SPC, will effectively unlock the full scientific potential of the NEWS-G experiment at SNOLAB and will allow the exploration of new dark matter interaction parameter space. Other sources of background that are particularly relevant to the search to low energy nuclear recoils from WIMP interactions are the cosmogenically produced tritium and carbon-14. Tritium and carbon-14 can be present in the detector with the gaseous targets, therefore special attention must be given to the pure gas source. Carbon-14 can also be found in the thin layer or carbonaceous compound that can coat the interior of the copper sphere. This can be mitigated with surface cleaning and etching in the presence of clean and dry nitrogen atmosphere. The backgrounds from the decay chain of radon-222 is also an issue for the NEWS-G SPC. Radon is typically emanated from gas purification units such as gas purifiers and filters. Radon contamination from the storage cylinders, detector plumbing and the gas itself is possible. A Research and Development program is currently being conducted in order to find the best techniques to remove radon. Radon mitigation can be achieved with radon trapping by using different methods (active charcoal systems, electrophoresis, etc.), or removed with distillation columns.

The Exposure Frontier With a good control on the radioactive backgrounds, a dark matter detector's sensitivity will scale with its exposure. Large target masses are therefore needed. In a SPC, large targets masses can be achieved with both by increasing the spherical volume, and by increasing the gas pressure. Hypothetically a factor 10 mass increase can readily be achieved in a 140-cm SPC installed in the NEWS-G shield at SNOLAB using pressure increase alone. The technical challenge with high gas pressures resides mostly in the SPC certification as a pressure vessel. For both increased pressure and increased volume, the issue of electron attachment to electronegative impurities can become a limiting factor. Electron attachment can be managed with enhanced control on the gas purity and by increasing the drift velocity at large radii using the ACHINOS sensors. These sensors equipped with small spherical electrodes would also provide for the strong electric fields that are needed near the sensor for gas amplification at high pressure. The spherical proportional counter (SPC) technology allows for a simple and robust solution to search for low mass WIMPs. The use of gaseous neon, helium and hydrogen targets is complementary to other experimental methods to search for low-mass dark matter particles using silicon or argon targets. Factor 10 improvement for both background levels and exposure are envisioned using fully electroformed spheres holding high pressure gaseous targets. The projected sensitivity of NEWS-G at SNOLAB is shown in figure 2 along side current limits and projections of other experiments searching for low-mass WIMPs. SPCs filled with low-pressure gaseous targets are also a promising technique for the directional measurement of nuclear recoil, which could assist at confirming a possible WIMP signal.

Name	Institution	FTE
L. Balogh	Queen's	0.5
E. Corcoran	RMC	0.2
G. Gerbier	Queen's	0.5
G. Giroux	Queen's	0.5
P. Gorel	SNOLAB/Laurentian	0.5
F. Kelly	RMC	0.2
R. Martin	Queen's	0.5
M.-C. Piro	Alberta	0.5
	Total FTE	3.4

Table 21: Canadian grant eligible investigators working on NEWS-G with corresponding FTEs.

5.9.2 The Canadian team and its impact

The FTE of faculty on the project are summarized in Table 21. The Canadian contributions and expertise are taking on several major components of the NEWS-G experiment.

- The Queen's group is responsible on several essential aspects of the research and development of the technology such as sensor, gas properties and dedicated calibration with sources and laser. The team is also in charge of the data analysis, simulations, and the measurement and analysis of the ionization yield (referred to as quenching factor, QF) of the nuclear recoil of Helium and CH4 at TUNL (Duke University, North Carolina). The mentioned measurements are crucial to determine the sensitivity of the detector to WIMPs of low mass. In addition, the group leads the project engineering and management which ensure the success of scientific goals of the project.
- The UofA group is in charge and responsible of the gas handling system including purifier, circulating turbine and gas analyzer. The quality of the active target is essential since contamination in the gas dramatically reduces signal amplification. A radon trap and online gas purity monitoring is currently being designed and tested. The group is also responsible of the data analysis for WIMP searches and the simulation of the electron drift which is essential for cut efficiency and the understanding of detector behavior. The team has a strong interest on exploring the possibility to add the directionality channel and plan to have dedicated R&D program to test this possibility.
- The SNOLAB/Laurentian team will be leading the installation, commissioning and operation of the experiment underground. As per SNOLAB requirement, all the NEWS-G activities underground will be overseen by an on-site supervisor and a project manager. The group is also in charge of the gamma simulation with GEANT4 and the slow-control.
- RMC (Royal Military College of Canada) is responsible of the Argon-37 source production which is crucial for the calibration of the detector at low energy.
- RMTL (Reactor Materials Testing Laboratory) is responsible to to develop a neutron beam facility able to reach even lower recoil energies for the quenching factor. The purpose is to have a Canadian facility to perform those measurements.

The NEWS-G team is now working towards installation and operation at SNOLAB.

Originally formed from groups at the University of Thessaloniki, in Greece, and at the Centre d'Énergie Atomique (CEA), in France, the NEWS-G collaboration grew quickly since 2014 when Prof. Gerbier was awarded the CERC at Queen's University. NEWS-G now involves 43 collaborators from 10 institutions located in 5 different countries. The member institutions outside of Canada are listed below.

- CEA IRFU, France
- Laboratoire du Physique Subatomique et Cosmologie (LPSC) / Laboratoire Souterrain de Modane (LSM), France

- University of Birmingham, United Kingdom.
- Aristotle University of Thessoniki, Greece
- Pacific Northwest National Laboratory (PNNL), U.S.A.

NEWS-G is a modest-size experiment that allows for HQP at all stages in their career to develop a wide range of skills, hardware and software related. Thanks to the important investment from the Canada Excellence Research Chair (CERC), Prof. Gerbier has established an ideal training ground at Queen's University. Several spherical detectors are in use at the Queen's University laboratory, where HQP can participate in all steps of the scientific method and get hands-on experience using state-of-the-art technology. We value effective communication and teamwork. All HQP participate regularly in several weekly global phone-calls or local meetings with members of the collaboration, or during our biannual collaboration meetings. During these meetings, the HQP are invited to present their work to their supervisors and their peers, and to participate in the discussions. These meetings are also an excellent forum for the HQP to rehearse their conference presentations. Faculty members generally have weekly or biweekly one-on-one meetings with the HQP they supervised, where they can discuss the progression of their research, professional career path, and specific barriers to success.

5.9.3 Required resources

Equipment and Infrastructure Needs The main background in NEWS-G is expected to come from the ^{210}Pb contamination of the copper in the bulk of the 1.4-metre SPC, more specifically from the bremsstrahlung photons from the beta-decay (endpoint 1.2 MeV) of its daughter, ^{210}Bi. Notoriously difficult to measure with conventional high purity germanium counters (minimum sensitivity >100 mBq/kg), the XMASS Collaboration has recently collaborated with NEWS-G to measure the ^{210}Pb content of our C10100 copper using an XIA. Four measurements over a period of one year were needed to disentangle the contribution of ^{210}Po from ^{210}Pb. Recent data analysis gives a contamination of 28.5$\pm$8.0 mBq/kg for ^{210}Pb in the bulk. Monte-Carlo simulations indicate that this contamination will correspond to a background of 1.5 events/kg/day/keVee, 5-times more than all other backgrounds combined. An expression of interest for a new opportunity at SNOLAB has started with the primary goal to build an intact copper sphere for the NEWS-G experiment by installing an electroformed copper production capability underground in SNOLAB. Ultimately, the pure copper production unit will be a SNOLAB facility to provide other users with the capability of making ultra clean copper pieces for next generation experiments such as nEXO, etc.

The justification for implementing the capability is that while commercial copper is one of purest materials used in underground rare event search experiments, it suffers from several limitations:

- Exposure of copper at the surface induces cosmogenic activation of radioactive species such as (^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co)
- Current commercial 4 to 4.5 N quality copper shows high contamination of ^{210}Pb. In the most demanding applications contamination of U/Th chain radioisotopes are also present at unacceptable levels.
- Form factors available require significant handling. In the case of NEWS-G spheres made from the process of forming hemispheres by spinning and welding are both contaminating processes.

Experience at PNNL has largely demonstrated that underground electroforming is the method for making the purest copper as of today, from the point of view of all contaminants listed above. Most mandrels used by PNNL to plate onto have been constructed from stainless steel. Based on PNNL's significant electroforming experience we are also confident that advanced material mandrel approaches will provide the capability of making the entire NEWS-G sphere intact without the need for welding and/or machining. This approach will be tested at PNNL prior to larger scale implementation at SNOLAB.

Technical Support Needs SNOLAB is the host institute for the dark matter search program using the 140 cm sphere. The facility provides access, space and utilities (electricity, water, IT, liquid Nitrogen for cover gas) for the experiment. It also makes avail- able to the project its support groups: Low Background Counting facility, Scientific Support group and Integration group.

SNOLAB is directly contributing in several aspects of the project. It supported a large portion of the cost of the lifting equipment required for handling and assembling the heavy pieces of shielding. A significant part of the seismic platform was also paid by SNOLAB. SNOLAB Integration group is building the setup required for the electropolishing/electroforming of the copper sphere and the Scientific Support team helps produce the etchant.

Computing Requirements NEWS-G data are stored on a server located at Queen's University. Currently, the storage amounts to 33 Tb, which is enough considering that a detector running in an above-ground laboratory produces roughly 1 Gb of data per hour, including raw and processed data. The server has 32 CPUs. We manage to share it with all the users across the collaboration. Most of the work does not require more than 1 CPU but some users doing simulation can sometimes use more the 32 CPUs for several hours. The team at the University of Alberta is investigating the possibility to buy a second server with similar characteristics to ensure that 10 CPUs are always available for all users. A scale up of NEWS-G in terms of number of active detectors and number of collaboration could imply multiplication of the computing capacity by a factor 3 to 5.

5.9.4 Outlook for the period 2027-2036

The competitive advantage of the spherical proportional counter to search for low-mass WIMPs will be maintained if the technology can be scaled to larger exposures, lower backgrounds, and made sensitive to lower WIMP masses. In case of a possible dark matter signal, the SPC technology allows in principle further background discrimination with a directional measurement in a large, low-pressure SPC equipped with a segmented sensor.

Copper electroforming of large spheres in underground environment will be required to hold larger gaseous target masses. Larger detectors will involve larger passive shields as well, possibly instrumented with active vetos. To drift charge over longer distances in large SPC high gas purity will be required. Sensor development is also key to provide sufficient drift field at long distances and amplification field near the sensor.

The measurement of the direction of nuclear recoils could allow for the confirmation of a WIMP signal. Using a multi-channel ACHINOS sensor with individual readout for each electrodes, a large SPC filled with low pressure gaseous target is a promising technique for the directional measurement of nuclear recoils. Multi-channel readout on ACHINOS is already being used to control the electric field uniformity, but nuclear recoil directional measurements remain to be demonstrated.

With other dark matter and neutrinoless double beta-decay experiments seeking for larger exposures and lower background, the electroforming of large copper vessel is set to be a technology that will be required outside of the NEWS-G collaboration.

The NEWS-G collaboration is seeking to increase its international participation. Through the SNOWMASS process we are hoping to attract collaborators in USA, and further involvement in UK is hoped 7 with a proposal to UK Research and Innovation led by the Birmingham group to build a 5-meter diameter SPC at the Boulby underground laboratory.

5.10 nEXO

The EXO (Enriched Xenon Observatory) collaboration operated a 200 kg detector to search for neutrinoless double beta ($0\nu\beta\beta$) decay in xenon. This experiment achieved significant sensitivity in the search for the $0\nu\beta\beta$ decay mode with the full analysis. nEXO is the next step in this progression, expected to increase the sensitivity to limits by a factor of more than 100, to or maybe beyond half-lives of 10^{28} years.

The nEXO collaboration is designing a roughly 5000 kg liquid xenon Time Projection Chamber (TPC) to search for the decay mode in ^{136}Xe. The use of xenon provides several advantages, not the least of which being the possibility for the tagging of the decays with Barium to unambiguously define them to be associated with a double beta decay.

5.10.1 Research Goals

The search for $0\nu\beta\beta$ probes several fundamental issues in particle and nuclear physics such as whether lepton flavour number is violated, the nature and scale of neutrino mass (*i.e.* is it a Majorana or self-conjugate particle), and the axial vector coupling in nuclear matter. It connects profoundly to other parts of the IPP program, such as the study of neutrino oscillations, in studying the fundamental properties of neutrinos and their connection to cosmological questions such as whether leptogenesis is responsible for the matter/anti-matter asymmetry of the Universe.

Name	Institution	FTE	Project
Razvan Gornea	Carleton	0.8	EXO/nEXO
Thomas Koffas	Carleton	0.1	
Bruce Cleveland	SNOLAB/Laurentian	0.2	
Jacques Farine	Laurentian	0.9	
Caio Licciardi	Laurentian	0.7	
Ubi Wichoski	Laurentian	0.4	
Thomas Brunner	McGill	0.95	
Jens Dilling	TRIUMF/UBC	0.2	
Reiner Kruecken	TRIUMF/UBC	0.2	
Fabrice Retière	TRIUMF/UBC	0.7	
David Sinclair	Carleton	0.05	EXO-200
Simon Viel	Carleton	0.3	nEXO
Erica Caden	SNOLAB/Laurentian	0.3	
Serge Charlebois	Sherbrooke	0.75	
Jean-Francois Pratte	Sherbrooke	0.75	
Marc-André Tétrault	Sherbrooke	0.7	LoLX
Daryl Haggard	McGill	0.1	Measurements
Ania Kwiatkowski	TRIUMF/UBC	0.2	Ba tagging
Total FTE		8.3	

Table 22: Canadian investigators working on EXO/nEXO, with corresponding approximate research FTEs for 2020/2021.

Specifically, the targeted outcomes for this project are:

- Irrefutable evidence for direct and explicit violation of lepton number conservation, and a new type of fundamental particle.
- Plausible connections to a new mass generation mechanism beyond the Higgs Boson, and a new class of right-handed neutrinos with very high mass.
- Compelling new window into the first moments of the Universe's expansion, and a possible explanation for the matter-antimatter asymmetry of the Universe.

This program is complementary to the other $0\nu\beta\beta$ searches such as SNO+. Having detection in different channels is an advantageous strategy to work toward eventual discovery.

5.10.2 The Canadian team and its impact

The Canadian group has had leadership roles for some time with EXO-200, including the senior analysis coordinator (Licciardi) and the manager for the operation and decommissioning (Brunner). These roles place the Canadian group in a good situation to continue on nEXO.

The Canadian group has also grown since EXO-200, adding an institution (Université de Sherbrooke in 2016) and several new members. This group has taken on significant responsibilities such as the management of photon sensors (Retière), radon emanation and trap (Farine) and the collaboration-SNOLAB interface (Caden). The Canadian contingent is also responsible for the delivery of the outer detector muon veto, the water circulation and assay systems, and PMT testing (Wichoski).

The Canadian group is detailed in Table 22.

5.10.3 Required resources

Support for the nEXO program has come from several different sources. An NSERC SAP grant supports the group but will be increasing in size as the deployment of nEXO approaches. The barium tagging is also supported by this grant. The NSERC RTI program has also been used to purchase equipment necessary for nEXO work, and continued applications are expected to be submitted.

The McDonald Institute has also supported the program and will continue to do so until the end of the institute in 2023 through both the faculty and the Venture Fund program. Support from CFI comes both through SNOLAB (funded by the CFI) and through the Innovation Fund and JELF programs.

nEXO will be counting on support from MRS facilities, particularly the joint machine shop use between Carleton University and the Université de Montréal. Continued participation from TRIUMF is also important, particularly through the development of the photodetector program. SNOLAB has also provided support through engineering support and conceptual design work. Support for personnel is also achieved through the SNOLAB research scientists. It is worth noting that nEXO has Gate 0 both at SNOLAB and at TRIUMF.

5.10.4 Outlook for the period 2027-2036

Commissioning and operation of nEXO is expected in late 2027 or early 2028 (assuming US DOE site and technology selection in 2020). nEXO is supposed to take data for at least one decade to reach its sensitivity goal of 10^{28} years. The Canadian team is dedicated to continue its involvement in nEXO and take leading roles in the operation and data analysis efforts. The team is committed to fully exploit the scientific reach of nEXO.

In parallel to the construction and operation of nEXO, an R&D effort will continue with the goal of reaching zero-background with isotope mass on the scale of nEXO and beyond. The solutions that are being pursued in Canada are tagging barium ions and a new technique for discriminating the signal from single electrons (due to gammas) and double electrons (double beta decay). The latter point involves detailed characterization of quanta production (scintillation, ionization and possibly others), which will be performed within the Light only Liquid Xenon (LoLX) collaboration in the next few years. Improvement in energy resolution through better understanding of the conversion of energy into quanta would also help with rejection of the two neutrino double beta decay. Breakthrough in quanta detection may be enabled by the use of the photon to digital converter (PDC) technology. An alternative approach to suppress backgrounds is by extracting a small volume surrounding a potential $0\nu\beta\beta$ decay event from the detector and probing it for the presence of a Ba-ion. Presence of the latter will unambiguously tag an event as true $\beta\beta$ event. Ba-tagging has the potential to eliminate all γ and β backgrounds. Furthermore, it will provide an independent verification of a potential positive signal.

5.11 SBC: Scintillating Bubble Chamber

The Scintillating Bubble Chamber (SBC) collaboration is designing and building a bubble chamber for the detection of both dark matter and coherent elastic neutrino-nucleus scattering (CEνNS). Using a target volume primarily composed of argon, the nucleation signal from electron recoils (the limiting factor for low-threshold studies in bubble chambers) is suppressed, allowing for the exploration of new parameter space.

5.11.1 Research goals

The SBC collaboration aims to build on the world-leading work of the PICO collaboration (Section 4.8), with whom a Memorandum of Understanding (MoU) has been ratified for the sharing of both experience and software. Currently, two detectors aimed at different physics goals, are being constructed. The first detector, under construction at Fermilab, will prove the feasibility of a large noble liquid bubble detector (a smaller prototype has already been shown to be viable). The second detector will be constructed and deployed at SNOLAB, and aims to have world-leading sensitivity to dark matter with mass between 0.5 to 5 GeV.

Following the collaboration focus on the SNOLAB installation, the re-commissioned first detector will be redeployed to a reactor site to investigate CEνNS. Collecting a sufficient sample of scattering events would improve the parameter discrimination significantly.

Once the first detector is functional, the lessons learned will be transferred to SNOLAB for the construction of the second detector. Prior to COVID-19 pandemic, the first detector was planned to be completed at Fermilab by the end of 2020 and the second detector installed in SNOLAB by the end of 2021. These timelines have shifted by at least four months. The first detector will be moved to a reactor, possibly at the Laguna Verde reactor in Mexico,

Member	Institution	FTE
K. Clark	Queen's	0.5
M-C. Piro	Alberta	0.5
C. Krauss	Alberta	0.1
P. Giampa	SNOLAB	0.5
Total FTE		1.6

Table 23: Canadian investigators working on SBC, with corresponding research FTEs.

for the CEνNS investigations.

5.11.2 The Canadian team and its impact

The international SBC collaboration includes 12 institutions, four of which are Canadian, seven American and one Mexican. Leadership of the collaboration is also shared between the countries, with a Canadian being the co-spokesperson. In terms of personnel, roughly one third of the people on the project are associated with Canadian institutions.

The Canadian SBC group has taken on a number of major responsibilities within SBC. These include all aspects of the scintillation detection system, background studies, piping and instrumentation, design and construction of the inner assembly, engineering support and modelling.

Students and postdocs on SBC have the opportunity to be involved in all aspects of the experiment. While SBC has only existed as a collaboration since August 2019, experience in groups such as PICO and other SNOLAB experiments highlights the high caliber of training experienced in similar projects.

The Canadian SBC faculty group is listed in Table 23.

5.11.3 Required resources

The SBC-SNOLAB detector is to be funded primarily by Canadians, with the full CFI JELF of K. Clark (roughly $500k) being designated to support this. The University of Alberta has committed to provide support for the construction of the gas panel, one of the vital pieces of infrastructure for the installation. An NSERC application was also submitted to support personnel, with positive news received in spring 2020. Through the combination of all of this funding, it is anticipated that the Canadian groups will be able to support the personnel to assist in the construction of both SBC detectors, with the hardware focus on SBC-SNOLAB.

The equipment needs for SBC are being addressed at the individual institutions, with a few exceptions. There is work being accomplished using the MRS shop at l'Université de Montréal, specifically to do a very delicate welding job for the jar bellows. The level of support from the individual institutions and the MRS shop should be sufficient for the construction of the first detector (SBC-Fermilab). The second, dark-matter-focused chamber (SBC-SNOLAB) will continue to use the Montréal MRS shop, but will also rely heavily on resources available at SNOLAB. These resources include not only the allocation of space in the underground lab (obtained by SBC in 2019) but also the use of several resources. In addition to the services used by all experiments (use of the cage, cleaning, transportation of materials, etc.) SBC is using the engineering resources as well. The team of engineers at SNOLAB have worked on designing not only required equipment for use underground, but also shielding which is vital to the successful operation of the detector. The SBC collaboration has also relied heavily on the resources and experience available at TRIUMF both for planning the use of silicon photomultipliers and also for the electronics associated with the acquisition of data from the detector.

The SBC collaboration has benefited from the use of Compute Canada (CC) resources, both in processing (for simulations) and in storage, using a default allocation. The needs are expected to grow but remain relatively modest; current projections are for 1.5 TB of storage for each year of livetime and 30 core-years for data processing needs, including simulation tasks.

5.11.4 Outlook for the period 2027-2036

The long-term plan for the SBC collaboration is to continue building on its research program, with a focus on low-mass dark matter detection and precision measurements of the CEνNS cross-section on argon and xenon. With such goals in mind, the collaboration is investigating a future tonne scale version of the SBC detector that would boost the sensitivity to the WIMP-nucleon cross-section by two orders of magnitude. This proposed SBC iteration would cover the remaining free-parameter-space down to the neutrino floor, or to further characterize a possible signal observed by SBC-SNOLAB. Moreover, the collaboration is also investigating the feasibility of studying even lower-mass dark matter candidates, by replacing the target fluid with lighter liquid noble gases (Ne, He, and H).

A tonne-scale detector would also strengthen the CEνNS program, given the proportional relationship between the expected CEνNS rate and the target mass of the experiment. Aside from a statistical advantage, the planned technical upgrades (see R&D strategy below) would also enhance this precision measurement, with lower internal backgrounds and boosted light collection capabilities. Further, the collaboration is planning on studying the effects of spin on CEνNS interactions, using liquid nitrogen as a medium instead of liquid argon doped with xenon. In parallel to securing a strong pool of resources (both HQP and technical support) through different funding agencies, the collaboration will also request further support from the hosting facilities. In particular, for the dark matter program, the collaboration will ask for both engineering and technical support from SNOLAB. This support will assist with the preparation of the assigned area, and with the installation of the detector on-site. Similarly, the collaboration will seek an equal level of support from the selected facility that will host the CEνNS program.

5.12 TUCAN

TUCAN (TRIUMF Ultra-Cold Advanced Neutron) seeks to make a new, precise measurement of the neutron electric dipole moment (EDM). TUCAN was formed by members of Japanese and Canadian institutes, using a unique spallation-drive superfluid helium (HE-II) ultra-cold neutron (UCN) source.

The most precise measurement of the neutron EDM was made at the Paul Scherrer Institute (PSI) in Switzerland, finding it to be consistent with zero $|d_n| < 1.8 \times 10^{-26} e{\cdot}\text{cm}$. The next generation neutron EDM experiments are now in preparation at a number of sites including TUCAN at TRIUMF, all seeking to improve the sensitivity by an order of magnitude.

5.12.1 Research goals

The neutron EDM has sensitivity to new sources of charge-parity (CP) violation, which could be caused by various sources of new physics including Supersymmetry, other extension of the Standard Model that could be responsible for the baryon-antibaryon asymmetry in the universe and CP violation in strong-force interactions. TUCAN has an uncertainty goal of $\delta d_n \sim 1 \times 10^{-27} e{\cdot}\text{cm}$.

The Cabibbo-Kobayashi-Maskawa (CKM) matrix also permits CP violation within the Standard Model (SM), but the SM prediction is five orders of magnitude below the reach of experiments. There is a large scope for the observation of physics beyond the SM in the neutron EDM.

5.12.2 The Canadian team and its impact

The TUCAN collaboration is formed from members from Japanese and Canadian institutes. The Japanese collaborators are responsible for the heart of the UCN source, the He-II cryostat which is the last and most challenging step of the UCN production. Canadians are responsible for implementing the cryostat at TRIUMF, and for the liquid deuterium neutron moderator system which surrounds the He-II production volume. Responsibilities on the EDM experiment are likewise shared. The Canadian collaborators are responsible for the magnetic shielding and magnetometers, the EDM measurement cells, UCN detectors, and data-acquisition systems. The Japanese collaborators are responsible for the UCN polarizer, external magnetic compensation system, and analysis software.

Canadians maintain leading roles in TUCAN. In 2016 TRIUMF operated a proton beamline with a D_2O cold neutron source. A vertical (prototype) UCN sources was used to produce the first UCN at TRIUMF in November 2017. By 2020, additional cryogenic tests of heat exchangers were completed, and the fabrication of the He-II cryostat is expected to be completed in 2020.

Name	University	FTE
Chris Bidinosti	Winnipeg	0.30
Beatrice Franke	TRIUMF	1.00
Michael Gericke	Manitoba	0.15
Blair Jamieson	Winnipeg	0.40
Elie Korkmaz	UNBC	0.70
Thomas Lindner	TRIUMF	0.35
Kirk Madison	UBC	0.10
Juliette Mammei	Manitoba	0.10
Russel Mammei	Winnipeg	0.60
Jeff Martin	Winnipeg	0.90
Takamasa Momose	UBC	0.20
Ruediger Picker	TRIUMF	0.80
Willem van Oers	TRIUMF/Manitoba	0.35
Total FTE		5.95

Table 24: Canadian investigators working on TUCAN, with corresponding research FTEs for 2020.

The medium-term plans of the experiment (2022-27) involve completing the UCN source upgrade, and constructing and beginning to run the neutron EDM experiment. In 2020-21, the new horizontal He-II cryostat will be shipped from Japan and installed at TRIUMF. The cryostat will undergo cryogenic testing thereafter. In 2022, the rest of the UCN source components will be installed, and first operation for UCN production will be conducted. The magnetically shielded room which will house the EDM experiment will be installed and characterized with precision magnetometers. In 2023, the EDM experiment will be assembled and commissioned, with running occurring for the next two to three years thereafter. The limits of the helium liquefier in the TRIUMF Meson Hall are expected to be reached within this period, and funding options for an upgraded liquefier facility are being considered. A CFI request toward the end of the five-year period is likely.

Presently, TUCAN collaborators in Canada supervise four NSERC-supported RA/PDF's, eight graduate students, and a number of undergraduate students throughout the year. They also have technical staff supported by CFI funds. The training received is extremely diverse. The experiment is also small enough that trainees can contribute to a broad variety of experimental questions. Recent projects have included beamline design, target design, neutron physics, neutron and radiation detectors, cryogenics, magnetometry, low-field NMR, laser physics, high-voltage design, data-acquisition systems, and computer simulation. The career opportunities for HQP trained in this fashion are also diverse. The possible industries range from the communications sector to nanofabrication, the semi- conductor industry, data analytics and computer programming, and medical physics.

TUCAN currently (2020) has 13 NSERC grant-eligible signatories with an FTE total of 5.95 as shown in table 24.

5.12.3 Required resources

TUCAN has been supported by CFI for construction, but has had to prioritize postdocs and research associates over students during the current construction phase of the project. The collaboration seeks to approximately double its Canadian graduate student cohort to 14.

The UCN source upgrade and EDM experiment were funded by the CFI infrastructure fund in 2017, with contributions from Japan and TRIUMF. The next major infrastructure need for the project will be an upgrade for increased helium liquefaction capacity at TRIUMF. The present UCN source is being designed with the intent that this upgrade will be completed at some point. The TUCAN group plans to make this request once the new UCN source has demonstrated high power functionality for briefer periods of time. The new facility would be required to obtain the full EDM statistics, enabling UCN source operation for sustained periods at the design beam current.

Compute Canada resources are used extensively for both Monte Carlo simulation and data analysis.

TUCAN receives technical support arranged with TRIUMF, generally budgeted as a CFI expense. TRIUMF houses the project and provides laboratory space for our TRIUMF-based scientists. The group is requesting one additional scientist or engineer from TRIUMF, to support the successful completion of the EDM experiment, and future experiments that may use the UCN source. TUCAN normally requests technical resources from the Carleton-UVic-Winnipeg MRS consortium. These are generally for the development of smaller infrastructure items requiring technical skills in detector fabrication, electromagnetic design and magnet fabrication, electronics, and cryogenics. A recent example of a project is that we are beginning to develop is an ultra-stable power supply for the main static magnetic field in the nEDM experiment. This power supply requires excellent (10 ppb) stability over hundreds of seconds (the timescale of the frequency measurement in the nEDM experiment). This is not a typical requirement faced by other experiments, and may require temperature control of elements of the power supply.

5.12.4 Outlook for the period 2027-2036

In the longer term (2027-2036), TUCAN will complete analysis of the EDM experiment, and may consider proposing upgrades if they are relevant to pursue. Data analysis of the EDM experiment will be ongoing throughout this period. The data will be blinded and analyzed by multiple groups. Upgrades to the EDM experiment could be considered in this period, and will depend on what is learned during the years of operation prior to this point.

A high-flux UCN source is being developed in support of the project. This may serve as a general purpose tool for other neutron experiments farther in future. The UCN source is planned eventually to become a user facility. The facility layout is designed with the idea of supporting two experimental locations, and other experiments that may use the second experimental port will be considered, such as a neutron lifetime experiment (V_{ud}, neutron lifetime puzzle), and a neutron gravitational levels experiment (extra dimensions, chameleon fields, short-distance modifications to gravity). The experiments considered will depend on the science priority and the experimental proposals received; a user facility where outside groups would submit experimental proposals to TRIUMF is anticipated, with the involvement of the present collaboration in developing the proposals. TUCAN would warmly welcome new collaborators interested in developing concepts for experiments that could be considered for this phase. The TUCAN project offers a local Canadian training ground in precision physics experiments.

6 Community Resources: R&D and Infrastructure

The success of the particle physics projects discussed in this document depends on the Research and Development of particle detector and particle accelerator technologies, as well as access to engineering and technical expertise. We also depend on computing and network infrastructure to distribute, process and analyze the enormous data sets acquired by particle physics experiments, as well as computing for simulations and other calculations. These techniques and resources are sometimes developed and deployed with specific projects in mind, but they can be used more widely, including on new projects, in other scientific fields, and in the private sector.

This section first described two R&D programs in Sections 6.1 and 6.2 which, while targeted, are potentially of wider interest. R&D in particle accelerators is then discussed in Section 6.3. More general engineering and technical support in our community, as well as funding for research tools and infrastructure, is documented in Section 6.4. Finally, the critical computing and network infrastructure needed by our field is described is Section 6.5.

6.1 Research and development for radiation-hard semi-conductor devices for tracking detectors in future collider experiments

The RD50 project performs research and development of semi-conductor, radiation-hard sensor devices that can withstand fluences of up to $10^{17} n_{eq}/cm^2$. It is motivated by the need to develop new technologies for tracking detectors to be used in experiments in future colliders beyond the anticipated HL-LHC. The proposed research will allow Canadian physicists to join the international effort for the development of such technologies, achieve knowledge transfer and train HQP in state-of-the-art detector technologies and eventually enable a new generation of Canadian researchers to develop a robust physics research plan that extends beyond ATLAS and the LHC.

6.1.1 Research goals

The international sub-atomic physics community have been working on the development of radiation hard semiconductor detectors for the LHC and the High-Luminosity LHC (HL-LHC) experiments for several decades. Canadian groups already play a significant role in the planned upgrade of the ATLAS inner tracker, the ATLAS-ITk. The research efforts presented in this brief will inherit the infrastructure developed for the ATLAS-ITk project in Canada. It will ensure continued use of a major Canadian subatomic physics investment and will result into new added-value in detector technology and know-how.

At present the focus is shifting towards evaluating the new challenges arising from radiation levels and technology demands anticipated for detector systems beyond the HL-LHC. This is primarily motivated by the proposed FCC (Future Circular Collider) project which has been identified as the next high-priority future initiative by the 2020 European Strategy Brief and the call in the same document to maintain a strong focus on detector R&D in order to be able to prepare and eventually realize experimental research programs. Canadian HEP groups are joining this new effort which is conducted within the framework of the CERN-based RD50 collaboration. The Canadian effort will be focusing on tackling three main aspects of the research needed for the development of the next generation of detector technology for future colliders. In parallel, potential applications within the HEP community and also commercialization opportunities can be pursued within the CERN-sponsored Timepix/Medipix collaboration.

6.1.2 The Canadian team and its impact

Canadian research teams will be making contributions to all three main aspects of the RD50 project: (i) radiation induced material defects and improved modelling; (ii) Silicon device characterization at extreme radiation fluences; (iii) new device structures and materials. This will ensure increased benefits from a research program that starts with understanding the physics of radiation induced effects to model/simulate them, follows up with mitigation efforts in a sequence of prototypes and eventually expands towards exploring new key structures and materials.

Most of the envisioned R&D will take place within the framework of the CERN RD50 collaboration. More immediate applications in the HEP community and beyond will be pursued under the sponsorship of the Timepix/Medipix collaboration, also at CERN. Canadian groups have established active collaborations with groups at RAL, Oxford, the University of Glasgow, the University of Birmingham, the University of Ljubljana, the Center for Microelectronics Research (CNM) at the University of Barcelona, the University of Freiburg, the Santa Cruz Institute of Particle Physics (SCIPP) and the Institute of Experimental and Applied Physics of the Czech Technical University. Our collaboration with NRC offers additional opportunities through NRC's agreement for collaborative research with Innovate-UK which is actively pursued by the groups at RAL/Oxford with UK-based industrial partners such as e2ν-Teledyne.

The Canadian group expects to occupy 2 post-docs/research associates and 4–5 graduate students for basic R&D work. This is roughly in line with the current ATLAS-ITk work experience in Canada. At least one additional HQP will be co-supervised with NRC researchers and partially funded by NRC internal resources according to existing shared supervision agreements with Carleton. It is anticipated that students will also work on physics data analysis and combined performance tasks within the ATLAS collaboration. This will allow them to be exposed to all aspects of experimental particle physics research and provide excellent opportunities to acquire a diverse set of skills desirable both in academia and in industry. Finally we anticipate at least two USRA/Co-op undergraduate students as well as students enrolled in the TRIUMF summer student program. Support from MRS, TRIUMF and NRC technical staff is described further below.

The Canadian faculty group working on RD50 is listed in Table 25.

6.1.3 Required resources

Research and development on radiation-hard device technologies directly builds on the equipment and infrastructure put in place for the ATLAS-ITk project in Canada funded through grants from NSERC, CFI and TRIUMF and indeed it ensures its continuous employment well beyond the timescale of the ATLAS-ITk project. More recently, additional funding was secured through an NSERC-RTI grant to procure a commercial grade DLTS system that will enable microstructural active defect characterization before/after irradiation of test structures. Significant funding will be needed to pursue the project with sources potentially including NSERC Discovery Grants and RTI requests. Through our participation in the RD50 collaboration, we are eligible for up to 200k CHF of internal CERN funding. Additional funding of up to $1M could be requested within the framework of the NRC and Innovate-UK agreement in 2018.

Name	Institution	FTE
Nigel Hessey	TRIUMF	0.5
Fabrice Retiere	TRIUMF	0.05
Bernd Stelzer	SFU	0.1
Matthias Danninger	SFU	0.1
Alison Lister	UBC	0.05
Claude Leroy	Montréal	0.05
Richard Teuscher	IPP/Toronto	0.1
Nikolina Ilic	IPP/Toronto	0.2
Claire David	York	0.1
Thomas Koffas	Carleton	0.35
Razvan Gornea	Carleton	0.1
Dag Gillberg	Carleton	0.05
Ryan Griffin	NRC/Carleton	0.1
Garry Tarr	Carleton	0.1
Total FTE		1.95

Table 25: Canadian investigators working on RD50, with corresponding research FTEs.

6.1.4 Outlook for the period 2027-2036

The international sub-atomic physics community has already started the process of evaluating the options and possibilities for a vigorous research program beyond the High-Luminosity LHC. There is a widespread consensus within the community that design studies for new accelerator projects with emphasis on pp and ee high-energy frontier machines need to be undertaken. Of particular interest to the research outlined here is the FCC project and the new challenges arising from radiation levels and technology demands anticipated during its realization. The FCC design is such that it could start as an ee collider (FCC-ee) evolving in time through a Z, Higgs, WW and $t\bar{t}$ factory by increasing the centre-of-mass energy from about 90GeV to 365GeV. In a second stage, the FCC will be turned into a $\sqrt{s} = 100$ TeV pp machine (FCC-hh), also suitable for heavy-ion collisions. This integrated FCC program would last 70 years from the start of the project implementation. It will enable a very rich physics research effort.

By the end of this decade the investigations of new technologies and materials for semi-conductor tracking devices, such as those outlined in the first section of this document capable of meeting the experimental requirements dictated by the FCC program, will be transitioning into the more focused R&D activities of an approved experiment, involving production/industrialization and then installation/commissioning of the technology of an operational tracking detector. Current experience from the work leading up to the HL-LHC detector upgrades indicates that the development cycle of a new technology is typically a dozen years or more. Therefore, with an anticipated timeline of about fifteen years after approval for realizing the first stage of the FCC program, the FCC-ee collider, the end of this decade would be the natural milestone where the transition towards a tracking detector R&D should occur.

In this new phase of the R&D program new challenges will have to be addressed characteristic of the design of a tracking detector system: occupancy which dictates in turn the granularity of the sensor elements; achieving low mass by minimizing the inactive material in the detector and which influences the overall tracking detector layout; coping with high data rates which informs the design of the on-detector readout electronics and of the overall DAQ architecture; achieving large sensitive area at low cost; and achieving large detector coverage at very low polar angles. Furthermore, the trend towards monolithic technologies also tends to blur the boundaries with ancillary components, such as read-out circuitry, and special care must be taken in optimizing them in combination with the sensitive components. Although proposed device structures such as depleted CMOS MAPS and LGAD devices, will go some way in addressing those challenges, this will not be enough. What will be required is the study of the performance of a fully laid out tracking detector system against representative physics benchmarks tailored to the specific operational parameters of the collider and in conjunction with other detector sub-systems under development, such as the calorimeters. This is an iterative process and significant effort will be necessary in order to achieve the combination of required performance. These type of undertakings can be successfully completed only by a properly constituted international tracking detector collaboration of a size similar to that of the ITk detector that Canadian researchers are presently involved in. The Canadian R&D program will not only facilitate the participation of Canadian researchers in such a future international tracking detector collaboration, but also

Member	Institution	FTE
Thomas Brunner	McGill	0.05
Mark Boulay	Carleton	0.05
Serge Charlebois	Sherbrooke	0.75
Jean-François Pratte	Sherbrooke	0.75
Fabrice Retière	TRIUMF	0.35
Simon Viel	Carleton	0.15
Total FTE		2.10

Table 26: Canadian investigators working on Photon Digital Converters, with corresponding research FTEs.

allow them to have a major impact and play central roles in the overall effort.

6.2 Photon to Digital Converter R&D and Silicon Photonics-based low power cryogenic (+room temp) data communication system

There is a desire for a coordinated effort towards the development of the photon-to-digital converter technology to serve the purpose of future low background noble liquid experiments. The dark matter and neutrino science experiments would greatly benefit from this breakthrough technology by pushing further their performances and discovery potential. In addition, we expand the project beyond the current scope to applications including tracking at colliders, detector using scintillating material at the EIC for example, and very large water Cerenkov detector such as P-ONE.

6.2.1 Research goals

The core of this project is the development of a technology for single photon and charged particle detection with applications in subatomic physics and beyond. It has recently become clear that the proposed technology can also be tailored to the detection of low energy electrons, minimum ionizing particle and heavy ionizing particle within the broader scope of this array of digital diodes (ADD) technology. We are indeed considering forming a proto-collaboration in Canada to support such a development. The ADD technology combines an array of diodes on a sensor chip (in silicon or other material) each connected to readout electronics on a separate chip (in CMOS technology) using a molecular bonding technology. Molecular bonding technologies are now mature and commonly used in industry. They enable the post-bonding thinning of the sensor or CMOS chips.

6.2.2 The Canadian team and its impact

Canada has a competitive edge in the ADD technology through the collaboration between Teledyne-DALSA (Bromont, QC) and l'Université de Sherbrooke (QC) for a photon to digital converter (PDC, formerly referred to as 3DSiPM). Indeed a front-side illuminated detector (FSI) is in development since 2017 (CFI supported, M. Boulay) in which Teledyne-DALSA provides the facility for the development of the photon sensor layer and the bonding to the CMOS with support from UdeS highly qualified personnel. The UdeS group is also leading the development of the CMOS chips and it has recently produced a fully functional prototype that is meeting the specifications of the nEXO and ARGO experiments for recording scintillation photons. SPADs are close to maturity and VUV enhancement is currently being studied. The readout electronics is validated and a new revision will enable full wafer production afterward. The 3D bonding is demonstrated on mechanical wafer and will be demonstrated with “real” wafers in the coming months. A back-side illuminated (BSI) configuration concept is being developed at TRIUMF and construction may involve an additional contribution from Teledyne-e2v (UK) for the backside processing. The work is performed in collaboration with UK collaborators, in particular Jocelyn Monroe at Royal Holloway University.

The faculty team working on photon to digital converters is listed in Table 26.

6.2.3 Required resources

The PDC and following ADD endeavor is expensive as it involves the development of new solutions which is inherently risky and requires new or upgraded facilities at Teledyne-DALSA or C2MI. Even though Teledyne-DALSA has a facility for molecular bonding this process has never been used for bonding SPAD arrays. Furthermore the SPAD array fabrication facility at Teledyne-DALSA is only compatible with 6" wafers while the molecular bonding facility requires at least 8" wafers. Significant industrial investment are therefore required. In addition, the technology readiness of the solution is overall relatively low even though, some parts, such as the CMOS chip are very advanced. Only front side illuminated SPAD arrays have been produced and the complete 3D integration process has not been fully prototyped yet. Nevertheless, very significant progress have been made in the last 3 years with the support of NSERC (EXO project, Pratte and Charlebois individual discovery), NSERC RTI (interposer development, Retiere), CFI (infrastructure for next generation noble liquid detectors) and the McDonald Institute (VUV sensitivity enhancement project and engineering support). The amount of funding received so far is about 3 M$. Another 2 M$ has been requested in the CFI IF 2020 competition within the contexts of ARGO and nEXO. However, we estimate that about 10 M$ will be needed for delivering a complete set of devices meeting all specifications, and for setting up the infrastructure enabling the production of more than 10 square metres per year. Therefore significant funding is still required. As mentioned earlier, one option is the collaboration with the UK that is very beneficial both technically (Teledyne-e2v has demonstrated state of the art performances for UV CCDs) and financially as we expect that funding from the UK can be used as leverage for securing funds in Canada. In addition, we are exploring the ADD global solution concept that could lead to a CFI grant application during the next competition. In general, PDCs are expected to have numerous commercial applications and we are exploring ways to attract partners for applied research funding programs. Even though the amount of funding required to support this program is beyond the scope of NSERC, NSERC remains a critical source of funding for HQPs in particular and for seeding new solution. However, NSERC SAP funding is very project specific while this technology tends to be cross-project. We are investigating the submission of a cross-project technology development grant as an NSERC project. This is the best use of money has the multi-project approach provides additional resources and maximizes the chances that the PDC solution will be used in many subatomic physics experiments.

6.2.4 Outlook for the period 2027-2036

With the possible exception of nEXO, PDCs will not have been used in a major experiments by 2027. By then, PDCs are expected to be achieving leading performances (efficiency, timing) for single photon detection from 120 nm up to near infra-red. Prototypes of digital hybrid photo-detector will also have been successfully deployed. Installation of 5 square metres of PDCs would also be nearing completion should the technology have been selected. Prototypes of digital LGADs would also have been tested. Nevertheless, the limits of the Array of Avalanche Diode technology capabilities in terms of timing, granularity and in situ processing are not expected to have been reached yet, because the focus pre 2027 would have been on sensor development.

By 2028, a number of projects maybe be using Array Avalanche Diode technology, including Liquid Xenon neutrinoless double beta decay and dark matter search experiments. The technology may also prove useful for large area water Cerenkov detectors, and possibly for trackers in collider experiments.

6.3 Particle Accelerator R&D

Particle accelerators have been critical to many ground-breaking results in the field of particle physics, both recently and historically. The energy frontier is mostly accessed with accelerators, which, for example, are used to create the high-energy, high-intensity beams at the Large Hadron Collider (LHC), producing the enormous number of proton-proton collisions needed for the discovery of the Higgs boson and for many other studies, including searches for BSM physics. They play a critical role also in neutrino experiments such as T2K, HyperK and DUNE, where very intense proton beams are needed to create the neutrino beams required by the experiment. High luminosity e^+e^- colliders were essential for the field both with the Z^0-physics programs at LEP and SLC, as well as the $\Upsilon(4S)$ programs at SLAC and KEK in establishing CP violation in the SM. The SuperKEKB e^+e^- collider at KEK set the new world record luminosity at 2.4×10^{34} $cm^{-2}s^{-1}$ in June, 2020 and this record will be steadily increasing over the coming decade. In Canada, accelerators are used for important experimental investigations of both fundamental symmetries and nuclear reactions relevant to astrophysics. In this field, TRIUMF is a world leader, with its Isotope Separator and Accelerator (ISAC) facility and its Advanced Rare IsotopE Laboratory (ARIEL). The TRIUMF cyclotron, besides providing proton beams to the ISAC target facility that produces the rare isotope beams, also provides beams used for the testing of detector components or the radiation testing of electronics, both of which are important to Canadian detector R&D activities.

Some of the particle physics projects with Canadian interests requiring accelerator research and development are discussed in Sections 5.1, 5.2 and 5.4.

A list of present and planned activities of the TRIUMF accelerator science community is provided in their submission, included as Appendix A. These include contributions to the HL-LHC upgrade at CERN and potential contributions to future machines, such as the ILC and FCC, and R&D for neutrino production. The TRIUMF accelerator team is also considering how to contribute to the Electron Ion Collider, including via crab cavity cryomodules, high brightness electron gun, hadron cooling, and beam physics models which include spin dynamics studies. The TRIUMF beam physics group is involved in spin dynamics studies in rings via contributions to the proposal to upgrade SuperKEKB with polarized electrons, which will benefit future engagement at the EIC. The Canadian accelerator science community also is involved in general accelerator R&D projects aimed at future facilities. These include the development of model based and model coupled beam tuning tools, development and testing of Superconducting Radio-Frequency (SRF) accelerating cavities, as well as efforts to develop new higher-gradient accelerating technoloiges, such as Plasma Wakefield acceleration, which TRIUMF scientists are pursuing within the AWAKE Collboration.

TRIUMF is also involved in training the next generation of accelerator physicists. TRIUMF has been offering an Accelerator Physics course through UBC and the University of Victoria with ten to twenty graduate students typically registering per year. Together with the Canadian Light Source (CLS) in Saskatoon, TRIUMF is planning additional courses to attract international students in Accelerator Science and in 2022, TRIUMF an CLS will bring the Joint Accelerator School to Saskatoon. TRIUMF has also reached out to other Canadian organizations that run particle accelerators or will host particle accelerators in the future to further organize Canada's Accelerator Science community and leverage that expertise in future projects.

6.4 Detector Development and Infrastructure

The development of novel technologies at the cutting edge of knowledge engages much of the time, effort and creative energy of experimental particle physicists. Consequently, it is essential for the field that the means to develop these tools and technologies be provided. This includes R&D on particle detectors, computing and networks, and particle accelerators. This section will focus on the detector development and general infrastructure needs of the field.

The overall need to maintain the infrastructure to build experiments is self-evident to experimental particle physicists. In Canada, in practice this means securing expertise at TRIUMF, SNOLAB, through the IPP Research Scientist program and from the personnel funded through the NSERC Major Resources Support program (MRS). Because these resources are so essential to the success of Canadian particle physics research, their support is of the highest priority for the community. Consequently, maintaining the MRS program within the SAP envelope is essential. Each of the MRS-funded initiatives can be highlighted for the essential roles they play, and IPP helps ensure they are resources accessible to the broader community by providing representation on their resource allocation boards and receiving annual reports from them at the IPP Annual General Meeting.

There are MRS funded personnel at the University of Alberta, Carleton University, the University of Victoria, the University of Winnipeg and l'Université de Montréal. In total, about 15 people are supported by the NSERC MRS program, including detector physicists, electrical engineers, mechanical engineers, electrical technicians, mechanical technicians, designers, and firmware experts. The TRIUMF Science and Technology department has about 20 members with a similar range of expertise, supporting both on-site and off-site projects.

The Arthur B. McDonald Canadian Astroparticle Physics Research Institute was formed in 2015, with funding from the Canada First Research Excellence Fund (CFREF). The McDonald Institute builds on the remarkable success of SNO and SNOLAB, ensuring that Canada remains at the forefront of international astroparticle physics. Among its activities, the McDonald Institute supports approximately 20 engineers and technicians contributing to all aspects of research, development, design, and construction of projects for Canadian astroparticle physics. The term of the initial CFREF award runs out in 2023, and the support of this technical team is vital for the long-term success of the program. Ideally the funding would involve the continuation of the CFREF award in some form, but this not normally possible; otherwise, possible sources could include enhanced NSERC MRS funding, increased SNOLAB operations funding, or perhaps contributions from other sources. Resolution of this issue is of high importance.

Access to the resources available via MRS-funded personnel, TRIUMF, SNOLAB and the McDonald Institute by the broader community is important to our overall success. Carleton, Victoria and Winnipeg have a common prioritisation board which allocates the resources based on community requests. TRIUMF has developed a "Gate-Review" process that provides an open mechanism for members of the community to access expertise and other TRIUMF resources while ensuring that TRIUMF manages its resources well and avoids over-extending itself. SNOLAB has developed a "Gateway" process that is similar to the TRIUMF Gate-Review process and the two labs are coordinating their efforts in supporting the community. The community would benefit by having more coherence in the overall allocation of resources from the MRS-supported personnel, TRIUMF and SNOLAB.

TRIUMF's engagement with the community was highlighted in the mid-1990's by an agreement between TRIUMF and NSERC that ensured that TRIUMF would only support projects that had NSERC funding or were approved to receive NSERC funding. The IPP community considers this agreement to be an important tool for coordinating the scarce resources available to researchers in Canada. IPP would like to see similar tools for coordination be developed between NSERC and CFI to ensure that CFI funds subatomic physics projects that are in line with the planning of the community as a whole given that the subatomic physics envelope is expected to carry the operational load.

In order to conduct the R&D on particle detectors that is required for the next generation of experiments, it is necessary that relatively modest amounts of funding be available in a timely manner for equipment. The NSERC SAP-Research Tools and Instruments (RTI) program is unique and essential in providing for this. The community places a very high priority on this program.

6.5 Research Computing and Digital Infrastructure

Computing is an integral component of subatomic physics research and its use ranges from medium to large scale computing; storage of large data samples; and the use of opportunistic cloud computing and high-performance computing for complex theoretical simulations. The computational and storage resources are linked with high-speed networks across Canada and to our international collaborators. The network enables enable us to communicate with our peers, e.g. via video conferencing, and transfer large volumes of data around the world.

Subatomic physics has been an early adopter of large-scale computing technologies, big data and distributed systems. Canadians have been very active in establishing computational resources, services and support within our universities and laboratories through initiatives with the Canada Foundation for Innovation (CFI) and Compute Canada. Most of the computing used by the community is managed by Compute Canada, a national not-for-profit corporation, whose members are the same research universities that host most Canadian SAP researchers.

Currently, the computing infrastructure used by the subatomic physics community consists of large Compute Canada shared facilities at four centres in McGill, Waterloo, SFU and Victoria. The SAP community is a large user of Compute Canada resources, and in the 2020 competitive resources allocation process, the SAP community has received an overall allocation of 18,129 core-years and 17.3 petabytes of storage (which is 26% of the overall storage allocated).

In addition, there is a dedicated large-scale Tier-1 facility at SFU/TRIUMF for the ATLAS experiment that is used to store and process the raw data in a timely manner from CERN. Since 2006, the Tier-1 has been funded via separate CFI awards, and is presently located in a Compute Canada facility at SFU. The Tier-1 centre was initially established at TRIUMF in 2007, then recently relocated to SFU in 2018, and continues to be largely operated by TRIUMF personnel.

6.5.1 Compute Canada & NDRIO

The Government of Canada has formally initiated a reorganization of the digital infrastructure in Canada. CANARIE will continue to manage and operate the research network in Canada as well as taking a leading role in cybersecurity. A new entity, currently called NDRIO (New Digital Research Infrastructure Organization), will re-organize and manage the research computing (currently done by Compute Canada), research software (currently managed by CANARIE and others) and data management (currently done by the users). NDRIO will take over the computing facilities and personnel of Compute Canada and the research software programs of CANARIE by March 2021. NDRIO is providing funding for upgrades and maintenance of existing Compute Canada facilities during the transition period.

In March 2020, NDRIO was formally established with a Board of Directors, followed by a search for a CEO in

June. The new NDRIO CEO was recently appointed (late 2020). A new governance model includes a researchers council that will provide key inputs to the board with respect to strategies and alignment with researchers needs. Most universities in Canada are full voting members of NDRIO whereas IPP, CINP, TRIUMF and SNOLAB are Associate (non-voting) Members.

NDRIO is expected to provide similar resources and services to the SAP community. Specialized and dedicated computing systems and services, such as the ATLAS Tier-1 and the proposed Belle II Raw Data Centre, have unique requirements (e.g. 24x7 support for the near-real time transfer of raw data and data reconstruction tasks). NDRIO, like Compute Canada, will not provide specialized systems; the projects are expected to request funds from CFI or other sources. The specialized systems are to be located in one of the Compute Canada data centres and Compute Canada personnel to provide help with operations. The SAP community has large needs, long planning horizons and is internally well-organized. As such, it is critical that the community plan for future computing requirements with the same diligence as for future accelerator and detector facilities. In the current environment, this means that the SAP community must be actively engaged in the development and prioritisation of the new NDRIO organization.

6.5.2 HEPNET/Canada

HEPNET/Canada has been responsible for national and international network connectivity for the subatomic physics community since 1990. HEPNET was established in 1990 and led by Michael Ogg (1990-1994), Dean Karlen (1994-2004) and Randall Sobie (2004-present). HEPNET is currently funded by NSERC with an MRS award (FY2020-2022). The community provides input to HEPNET with an advisory committee who are appointed in consultation with the IPP Director. The members are R. Moore (Alberta), C. Jillings (SNOLAB) and A. Warburton (McGill).

HEPNET coordinates the network for the HEP community and works with CANARIE, the provincial network organizations and Compute Canada to link our laboratories and universities to each other and the international community. HEP is the largest user of the CANARIE network.

Currently, the network backbone across Canada has two 100 gigabit/second links (100G) between Victoria and Montreal, and four 10 gigabit/second (10G) links to east coast. The plan over the next few years is to add a third 100G link across Canada and to increase the capacity of each link to 200 gigabit/second.

Canada is well connected to Europe and Asia. CANARIE, and its partners Internet2 (USA), ESNet (USA), NORDUnet (European Nordic countries), GEANT (Europe) and SURFnet (The Netherlands), completed a redundant mulit-100G ring, called ANA (Atlantic Network Architecture), between four exchange points on both sides of the North Atlantic. Canadian researchers also have access to a multi-100G trans-Pacific link with ESNet.

A large fraction of the network traffic is associated with the international projects. The LHC experiments have two networks for moving data. The first is the LHCOPN (Large Hadron Collider Optical Private Network) that connects the CERN Tier-0 (T0) centre with each of the Tier-1 (T1) centres around the world. The second network is the LHCONE (LHC Open Network Environment), a private routed network that links all the major centres.

The LHCOPN provides dedicated point-to-point connections (often called lightpaths) from the T0 to each T1. ATLAS has ten T1 centres including one at SFU (some equipment is still operational at TRIUMF). CANARIE provides a 20G dedicated connection to CERN for the LHCOPN link. The primary purpose of the LHCOPN network is the transfer of raw data from CERN to the T1 centres. The LHCONE is designed to allow routed traffic between any site and isolates the HEP traffic from the general research network. As many LHC computing centres also provide resources to non-LHC experiments, the LHCONE is now used by other experiments such as Belle II and DUNE. The major Compute Canada centres (used by the HEP experiments) are connected to the LHCONE network.

The computing resources for the LHC and other experiments are globally distributed and rely on high performance networks. Experience has shown that identifying and resolving network issues can be difficult due to the lack of tools and information, and the many administrative domains. A key step in improving the situation was the selection of the perfSonar (Performance focused Service Oriented Network Monitoring ARchitecture) system by the WLCG community (HEPNET participated in the selection and evaluation process). Nodes for bandwidth and latency measurements are deployed at the T0, T1 and T2 sites around the world. The nodes at each site perform a number of network tests, such as bandwidth tests every few hours or latency tests every minute. HEPNET has deployed a set of nodes at the Canadian ATLAS Tier-1 and Compute Canada sites. The nodes were delivered directly to each site and configured with the assistance of HEPNET.

A key role of HEPNET is to anticipate and help develop tools to utilize the increasing network capacity (which doubles every 24 months). HEPNET has participated in high-speed network demonstration projects with our national and international partners for many years. The projects usually involved industry, who often provide access to new server and network technologies. HEPNET will continue to participate in these projects in the 2022-2026 period.

The Canadian team and its impact HEPNET has an excellent track record of training technical staff, and graduate and undergraduate students. A large fraction of the HQP is supported by non-NSERC funds. HEPNET has employed over 50 undergraduate science, computer science or engineering students (approximately 15% are female students). One or two students are employed every four-month term. The students return to their studies after working with the group and most find a position with industry after their graduation. Their exposure to networks and cloud computing is viewed as an asset by potential industrial employers.

HEPNET works with CANARIE, BCNET, Cybera and other Canadian network organizations to ensure the network meets the requirements of our projects; and also represents Canada on international network policy and technical meetings

Required resources HEPNET uses a fraction of its MRS award to pay for a variety of small network equipment or port charges; and contributes to the lease of the network that connects SNOLAB to the local network provider.

HEPNET has a strong relationship with the network and computing industry. For example, HEPNET has a small in-kind grant for cloud resources on Amazon EC2.

Outlook for the period 2027-2036 Historically network capacity doubles every two years and it is expected that this trend will continue for the foreseeable future. Assuming this prediction is correct, we should expect terabit/second networks (1000G) in this period and computing centres will have multi-100G or 1000G links to the national backbones. We believe HEPNET will continue to have an important role for the subatomic physics community for the next 10 years (and beyond). The change to 100G networks has had a significant impact on the movement of LHC data and we similarly expect that terabit/second networks will result in considerable changes in our computing models. For example, a 1000G network will mean it no longer matters where the computing facilities are located in relation to the data. In the next decade, we envisage HEPNET continuing its role of coordinating production networks required for our operational projects and developing the expertise to exploit the terabit-scale networks and computing technologies for our future projects. Our vision is that HEPNET will continue its strong collaboration with our national and international research partners as well as industry in this area. HEPNET will continue to exploit its unique niche for obtaining non-traditional support that will augment our NSERC support. These activities will continue to make HEPNET an excellent project to attract and train exceptionally talented staff and students.

7 Equity, Diversity and Inclusion

Issues surrounding the lack of Equity, Diversity, and Inclusion (EDI) in particle physics have rightly come to the forefront of current discussions. We realize that the best science is done by groups that are inclusive, diverse, and act in an equitable manner. We are striving to improve in these areas, and are committed to addressing the structures that cause these systematic problems. The following sections review the existing policies and programs to promote EDI in Canada, calling out successful initiatives of certain groups. We realize the challenges to achieving EDI and lay out goals for our field.

7.1 Demographics of Canadian Particle Physics Community

The Canadian Association of Physicists (CAP) is carrying out the first survey of demographics and experiences related to EDI in the Canadian physics community. The data from this and future surveys will be invaluable inputs for the Canadian particle physics community's mission to create an equitable, diverse and inclusive community. The data will be used to identify deficiencies in the community's approach to EDI and the efficacy of programs and efforts undertaken by the community in order to improve EDI. The reader is referred to the results of the CAP survey.

7.2 Systems and Policies to Promote Equity, Diversity and Inclusion

Canadian scientists work with policies and systematic structures, both at the institutional and scientific collaboration level, that are designed to promote diverse and inclusive research environments. Since many scientists in the field of particle physics collaborate on experiments with tens, hundreds, or even thousands of participants, these scientific collaborations have their own leadership structures and policies. Examples of how Canadian scientists use institution and collaboration policies and structures are highlighted here.

Almost all scientific collaborations report using resources provided by EDI committees as their home institutes to promote diversity. In particular, home institutes may provide training for hiring practices, such as unconscious bias training, and hiring policies that are applied when filling studentships or postdoctoral positions.

Many scientific collaborations report having their own Codes of Conduct that are used to define acceptable behaviours and practices within the collaborations to promote equitable, diverse and inclusive environments. Furthermore, a number of collaborations fill specific positions that are responsible for promoting inclusive environments within the collaboration, while acting as contacts for reports of discrimination, bullying or harassment. For example, the Belle II experiment has two diversity officers, while SNO+ and the Scintillating Bubble Chamber experiment have ombudspersons. For the case of SNO+, two out of four ombudspersons are early career scientists.

Many large collaborations, such as ATLAS, T2K and Belle II have their own diversity committees or EDI working groups that are tasked with defining and encouraging policies to ensure equitable, diverse and inclusive environments. In the case of the ATLAS experiment, Canadian faculty were instrumental in the creation of the diversity committee, established in 2017. Canadian leadership within the IceCube experiment was also instrumental in establishing collaboration EDI policies. In addition to formal structures, experiments such as IceCube and T2K have regular meetings or networking events where women and other underrepresented groups can meet, or issues facing women and other underrepresented groups are discussed.

Some Canadian research groups track diverse representation, although comprehensive tracking with surveys of self-identification are not yet common. The ATLAS-Canada group, for example, tracks the fraction of male and female scientists and their participation in activities such as leadership positions and conference talks, and compares the Canadian data to the ATLAS collaboration at large. Currently both the ATLAS-Canada group and ATLAS collaboration do not collect data on how collaborators identify by race, colour or ethnic origin, but they will investigate ways to collect this information.

Many collaborations have explicit policies to ensure diversity within leadership positions or for conference talks. The DEAP-3600 collaboration has 1-year long terms for leadership positions, and fills these positions with graduate students and postdoctoral fellows, ensuring that all early career researchers have the opportunity to fill research roles. Within the Belle II collaboration, it is the responsibility of the diversity officers to ensure that marginalized groups are considered for positions of responsibility, and within the SNO+ collaboration, analysis working group leaders are chosen while taking diversity into account.

7.3 Programs to Promote Equity, Diversity and Inclusion

Programs to promote equity, diversity and inclusion (EDI) vary across the country. Many of the institutions are signatories of the Dimensions Charter, an initiative of the three granting agencies in collaboration with universities, colleges, and institutes Canada to promote EDI in their environments and across the research ecosystem.

Many institutions host public lectures, which are aimed at explaining science to all. Science Rendezvous Kingston has been a large and popular annual event in Kingston. Attended by thousands of families and members of the local community, Science Rendezvous has a variety of displays, exhibits, demonstrations, experiments, hands-on activities and presentations which actively engage the public in learning about science. This award-winning event has major community sponsorship in conjunction with strong support from Queen's University.

Many administrations have instituted mandatory equity and inclusion training for faculty, as well as additional diversity training for hiring committees. To promote equity and gather a diverse group of HQP at all ages, programs can be broken up into ones that focus on secondary schools, undergraduates, and graduate students.

Middle and High School Students The GIRLS Initiative (Girls for Innovation, Research, Leadership & Science) was started in 2019 at Queen's by graduate students, who conceived, led, coordinated and carried out a science summer camp for girls between the ages of 11-13 to promote and develop an interest in STEM earlier than high school. For 2020, the instead of an in-person camp, new activities include social media interviews with women scientists and running the Canadian Online Science Fair, which was open to all genders and featured a female mentor for each project entry to work with the students. There are future plans to launch GIRLS Initiative programs (e.g. summer camps) at other institutions across Canada, in addition to these online offerings.

The Verna J. Kirkness Program brings high school Indigenous students to various campuses across Canada for a week in May to participate in scientific research. Faculty and their students at University of Victoria, UBC, and University of Manitoba are mentors in the program.

The University of Alberta has an exceptionally effective Women in Scholarship, Engineering, Science, and Technology (WISEST) initiative that funds summer research positions for women and other underrepresented groups currently in high school to encourage their recruitment into STEM fields.

Undergraduate Students Women in Physics Groups exist at many universities and play a strong role in creating community, give students the opportunity to discuss barriers they may face, and encourage other under-represented groups to pursue STEM fields.

University of Winnepeg led a new PromoScience application to NSERC for a program to encourage Indigenous undergraduate students in the sciences toward careers in graduate school.

The Grenfell Campus of Memorial University of Newfoundland is a center for scientific and cultural outreach for youth in the Western Newfoundland region, especially rural, female, and Indigenous students. The program features female and Indigenous role models, discuss career opportunities, and emphasises a diverse set of skills required in modern science such as cooperation and communication.

Graduate Students & Faculty Graduate departments also host "Women in Physics" groups that serve the same goals as those for undergraduate students. Merging the groups can provide mentorship opportunities that benefit all invoved.

The IceCube collaboration hosts "Women and Allies" and "LGBTQ and Allies" networking events at their collaboration meetings. These promote networking within and between different EDI communities and the collaboration at large, providing a welcoming atmosphere for new collaboration members.

Some collaborations have "Speakers Committees" that consider the career development of young scientists, diversity, and geographic representation in the assignment of conference talks.

7.4 Challenges to Achieve Equity, Diversity and Inclusion

Particle physics research in Canada includes participation in experiments carried out in other countries, where laws and host institute policies may be inequitable or exclusive for some Canadian researchers. For example, host laboratories in some countries may deny physical and/or electronic access to the laboratory based on the country of origin or citizenship of researchers. When faced with these exclusionary policies, Canadian researches have taken measures to mitigate the exclusion where possible. While the lack of physical access cannot be fully mitigated, the lack of electronic access is mitigated by hosting copies of all experimental data in Canada, and providing access to necessary computing resources in Canada. Steps to mitigate inequitable and exclusionary policies outside Canada will typically require additional resources, and it is important that the P.I.s addressing these issues have access to the funding necessary for mitigation.

Canadian researchers carry out policies and engage in training with the aim of implementing hiring processes that will increase diversity within the field. While hiring policies and practices can have a positive effect, increasing diversity in the pool of applicants is also important. Programs to increase diversity in the STEM fields early in the education process are necessary to realize diverse applicant pools for undergraduate researchers, graduate researchers and postdoctoral fellows. Some researchers in the particle physics community are engaged in programs to increase diversity at the secondary education level. Increased organization and engagement of the particle physics community at this level may lead to better outcomes for increased diversity in the field.

7.5 Goals for 2022-2026 Period

As a community, we must continually work to improve our equity, diversity, and inclusion in the field. We can do this by raising the profile of EDI efforts in the community and fully engaging in those efforts. We can share the best practices that institutions and collaborations have developed. It is not enough just to invite a more diverse group of people into our universities, but we must make sure that those universities have equitable and inclusive policies to retain them.

We can continue to gather and share the outreach opportunities in which our members participate, to increase their visibility and broaden their impact. A regular survey of the demographics of the community will let us know if these efforts have borne fruit, or if we have to change out tactics. We look to the CAP to gather this information.

The IPP sent a survey to its members, asking a variety of questions, including ones about the policies and practices that are used to support an equitable, diverse and inclusive research team environment and what methods are used in the recruitment of a diverse group of HQP and an inclusive training environment. Ideas offered focus on creating open and inclusive atmospheres in research groups, recruiting students as well as speakers from diverse groups, and discussing unconscious bias with TAs and graduate students. Many quoted the Canada Research Chair guidelines and best practices when hiring. What is also stressed is the interaction of existing HQP during recruitment. All of these are steps that everyone can implement in their own groups to improve equity, diversity, and inclusion in our field.

8 Broader Societal Impacts

The Canadian particle physics community engages in many experiments that require new and innovative technologies that often have applications in industry, medicine and other fields of science. Many experiments require direct engagement with industrial partners to realize innovative detector systems, and this engagement often leads industrial partners to expand or refine their capabilities.

Canadian particle physics experiments and laboratories have been engaged in the initial use of silicon photomultipliers (SiPMs) and their further development. Canadians institutes were leaders on the T2K near detectors, one of the first large-scale applications of SiPMs, which started operation in 2010. The SiPM technology will be used by the particle physics experiments, including nEXO, DarkSide-20k, Scintillating Bubble Chamber and MATHUSLA.

Université de Sherbrooke and TRIUMF are leading the development of new SiPM detectors that include photon-to-digital converters (PDCs) integrated in the same package as the SiPM. This work is carried out in close collaboration with Canadian company Teledyne DALSA. Expected broader applications of this technology include, but are not limited to, time of flight positron emission tomography, computed diffuse tomography, 3D imaging, microscopy and air/gas analysis. The PDC technology has applications to future experiments, including the ARGO dark matter experiment and subsequent phases of nEXO.

The ATLAS experiment collaborates with Celestica for the construction of the Canadian contribution for the silicon-strip modules of the ITk, and with DA-Integrated on the probing and dicing for 50% of the ITk readout ASICs. So far, DA-Integrated is the only company that has qualified to do this work and has been invited to take part in the CERN Market Survey, which is part of the procurement process for the remaining 50%.

Canadian researchers are further engaged in the development of silicon sensors through the RD-50 collaboration. This endeavour is driven by the need for better fabrication techniques resulting in reduced material defects, which also forms the underlying theme for applications such as enhanced light sources (improved diode lasers), radiofrequency devices (next generation of 5G devices), nuclear technology (nuclear reactor operation monitoring) and operation in harsh environments such as those encountered in deep space missions. The RD-50 collaboration's relationship with the Timepix/Medipix collaboration, one of CERN's main vehicles for technology transfer to industry and the broader society, provides unique opportunities to contribute to on-going application and commercialization efforts. For example radiation-hard Timepix-2 devices were adopted by NASA to visualize the radiation environment on the International Space Station and in deep space aboard the Orion Exploration Flight Test-1 (EFT-1) in 2014.

The SNO+ experiment has partnered with CEPSA Quìmica Bècancour for the production of linear alkylbenzene (LAB). Based on the transparency requirements for SNO+, CEPSA adopted a special mode to produce the LAB, and this applied for other experiments such as Daya Bay, RENO and JUNO. The higher transparency LAB also has commercial applications. SNO+ also collaborated with Seastar Chemicals for the purification of telluric acid to achieve the necessary Tellurium purity, in the processes expanding Seastar Chemicals capabilities. SNO+ worked with Plasticon Canada to develop new clean manufacturing techniques for fiber-reinforced plastics (FRP), which is in increasing demand for the production of process systems for the semiconductor industry, and was previously only available in North America through a U.S. company.

The detection technologies for particle physics experiments often have applications in nuclear reactor operation monitoring. The water Cherenkov gadolinium sulfate technology planned for the Hyper-K Intermediate Water Cherenkov Detector has applications for long-range nuclear reactor monitoring. The measurement of coherent neutrino scattering with spherical proportional counters (SPCs) developed by NEWS-G could lead the way to a compact and non-intrusive technology to monitor nuclear reactor and international nuclear safeguarding. The SPCs also have applications in low-level radon measurement, neutron spectroscopy and gamma spectroscopy. In addition, University of Alberta is working on the development of a sensitive way to monitor CH_4 concentration which can be used for greenhouse gas sensing applications. The dark matter detection technique used by PICO was born out of an industrial application, neutron dosimeters based on bubble detectors developed at BTI in Chalk River. The PICO collaboration has identified neutron dosimetry and low background methods as potential areas of interest for industry with possible future applications.

The cyrogenic calorimeter technology of SuperCDMS has applications particles physics and astronomy research with features that may make them desirable for specific applications in industry. A low-background cryogenic environment may be of interest for understanding coherence times in quantum computing applications. SuperCDMS and CUTE are open to collaboration with, and the use of their unique facilities and technologies by international and industry partners. SuperCDMS has also partnered.

MOLLER collaborators are collaborating with researchers in the biosciences who are investigating the growth behavior of fungi and other plants under extreme environmental conditions by working on the customization of MOLLER electronics design to produce a small DAQ system that can be deployed in a remote area, to monitor environmental data (such as UV exposure, continuous tracking of small variations of light, temperature, humidity, etc.).

8.1 Highly Qualified Personnel

One of the benefits of training excellent particle physics students is the impact they have in the world after they are no longer our students. We list here a small selection of stories of our highly qualified personnel (HQP), which provides a taste of the types of impact the field has in training them.

Zach Barnard (MSc 2013, Laurentian, SNO+) Barnard completed his MSc at Laurentian, and then worked as a cryogenic technician at SNOLAB on the DEAP-3600 experiment. He is now at Bluefors Oy, a cryogenic technology company in Helsinki, Finland.

Simon Caron-Huot (Ph.D. McGill, Theory) Caron-Huot completed his PhD where he studied hot and dense systems, including the quark-gluon plasma. He is currently an Assistant Professor and CRC at McGill, and he received the 2020 New Horizons Prize in Physics for "For profound contributions to the understanding of quantum field theory."

Alexandre Beaulieu (Ph.D. 2019, Victoria, Belle II): For his MSc, Alex published on a search for evidence of a dark sector particle in BaBar data before measuring and modelling accelerator backgrounds in SuperKEKB for his PhD. During his PhD he designed and oversaw the fabrication of radiation shields to protect the Belle II endcap calorimeters from beam-related photon and neutron background. This project included stainless steel, cast lead, and polyethylene, and led to an expansion of the capabilities of the selected vendor. He is now in Montreal working as the Regional Director of LTI Informatique et Génie (Software + Engineering), an engineering consultancy firm. He states on LinkedIn that his "personal goal is to enable manufacturing industries harness applied science to boost their productivity. I reach toward this goal through championing communication across specialties and promoting efficient, tailor-made, software development and R&D workflows."

Djuna Croon (Postdoc, TRIUMF, Theory) Croon is currently finishing a postdoc at TRIUMF where she has pioneered the field of using gravitational waves to probe physics beyond the Standard Model. In 2021 Djuna will begin a faculty position at the Institute for Particle Physics Phenomenology in Durham, UK.

Sean Hansen-Romu (Ph.D. Student, Manitoba, TUCAN) Handsen-Romu is an Indigenous grad student whose research is focused on UCN polarization and analysis, and UCN detection. A remarkable aspect of Sean's outreach efforts is that he is involved as an instructor in the Pathways 2 Grad Studies program at UWinnipeg. This is a program at UW that encourages early-career undergraduate Indigenous students toward careers in scientific research.

Lindsay Forestell (Ph.D. 2019, UBC/TRIUMF) Forestell's research focused on dark matter and the impact of new particles and forces on cosmological observables. In addition to the direct quantitative analysis skills she obtained in her degree, she also developed competency in machine learning and data science through a TRIUMF computing training program. After graduation she transitioned to industry, beginning with a contract position as a Data Scientist with White Box Analytics in Vancouver. She accepted one-year data science fellowship with the BC provincial government aimed at helping incorporate data science into more ministries. This fellowship led to a permanent position as a Research Officer with the BC Ministry of Education, with duties ranging from operational data systems management to research proposals for new areas of study to supporting the school districts with data and analysis.

Nikolina Ilic (Ph.D. 2015, Toronto, ATLAS) Ilic first started with ATLAS-Canada as an IPP summer student in 2008 and completed a ATLAS PhD the University of Toronto in 2015. This was followed by postdoctoral work at Stanford University until 2018, when she was hired as an Assistant Professor at the Radboud University in Nijmegem, Netherlands. A year later she was attracted back to Canada where she was hired as an IPP Research Scientist and an Assistant Professor at the University of Toronto, working on ATLAS and DUNE. She maintains an academic appointment in Nijmegen and also co-supervises PhD students at institutions in Kenya and Nairobi.

Belina von Krosigk (PostDoc, UBC) Von Krosigk has become an indispensable resource in the collaboration. In addition to managing the development of the DAQ software for SuperCDMS SNOLAB, in her role as analysis coordinator she has transformed the collaboration's approach to producing physics analyses. Her efforts have approximately doubled the collaboration's publication rate with 8 publications since 2018 while strongly supporting the training of graduate HQP in the collaboration. von Krosigk has successfully transitioned from the North American academic environment into leading her own research group on SuperCDMS at the Universität Hamburg and DESY.

Pawel Mekarski (Ph.D. 2018, Alberta, SNO+) Mekarski held a Vanier PGS at Alberta. He won the 2017 CAP Congress PPD 1st place oral presentation award. His thesis was on a search for reactor antineutrinos in the SNO+ water phase. Mekarski is now employed at the Radiation Protection Bureau of Health Canada as a Radiation Coordination Specialist.

Andree Robichaud-Veronneau (MSc, ZEUS; Postdoc, ATLAS, McGill) Robichaud-Veronneau started in particle physics as undergraduate summer student at McGill, working on data acquisition electronics for a spark chamber. She later became a McGill MSc student on ZEUS, spending most of her time at DESY. She did a PhD at the University of Geneva and a postdoc at Oxford, before returning to McGill to work, from 2014–2017, on the ATLAS New Small Wheel project, where she was instrumental in setting up the lab for the sTGC cosmic-ray testing. She is now with Ciena, a Telecommunication company in Montréal, as Data Scientist. She has recruited another ATLAS-Canada trained HQP Lévis Pepin, who did an ATLAS MSc at McGill. She writes in her LinkedIn page: "Particle Physicist by training, delving into the telecommunications world and applying statistical and data analysis concepts to the industry and customer needs." and "Software development and machine learning for the Telecom service industry."

Doug Schouten (Ph.D. 2011, SFU, ATLAS) After completing his Ph.D. Schouten worked for three years as an ATLAS Research Associate at TRIUMF. In 2014 he took a position working for CRM Geotomography Technologies, at that time a tech-transfer spin-off company working out of TRIUMF. He rapidly rose to the position of Chief Technology Officer, and has been a key member of the team that has brought the company to full independence

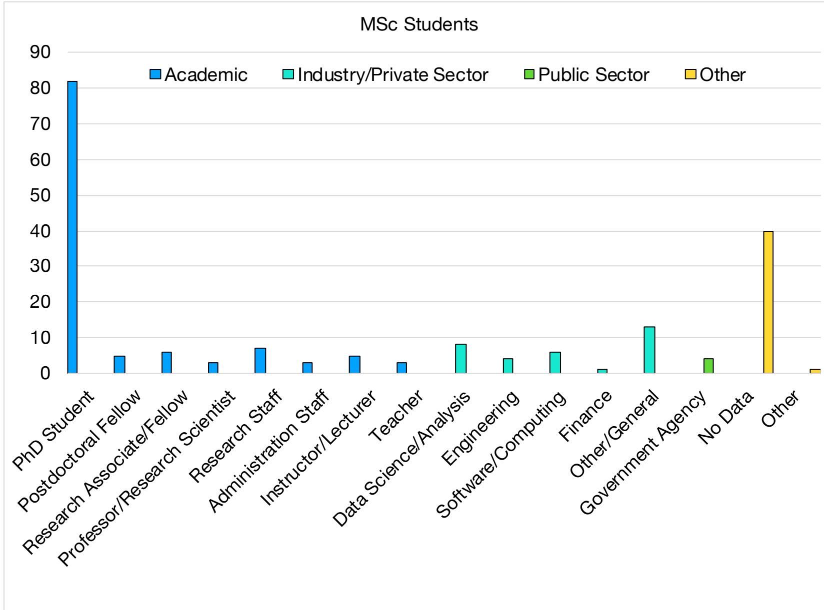

Figure 2: Current positions held by former MSc students that participated in particle physics experimental projects in the last decade.

as Ideon Technologies Inc, based in Richmond BC. Ideon is a world pioneer in the application of cosmic-ray muon tomography, with a discovery platform integrating proprietary detectors, imaging systems and AI techniques to provide X-ray-like visibility up to 1 km beneath the Earth's surface. By transforming the data into geophysical surveys and 3D density maps, Ideon helps geologists identify new mineral and metal deposits with precision and confidence, reducing cost and minimizing environmental impact.

Rocky So (Ph.D. 2015, UBC, BaBar) So's dissertation was on Light Higgs searches at BaBar. He is Data Scientist at Softmax Data, a consulting firm, and at Delecta Technologies, a start up, both based in Vancouver. In one of his projects, he worked with Technical Safety BC to develop methods to identify abnormalities in elevator operations using internet- connected accelerometers, a project that was beyond the capabilities of the in-house data scientists.

Information about the career paths and outcomes for HQP who have worked on Canadian particle physics experimental projects in the last decade have been collected. They are summarized for MSc students, PhD students and Postdocs/RAs in Fig. 2, Fig. 3 and Fig. 4 respectively.

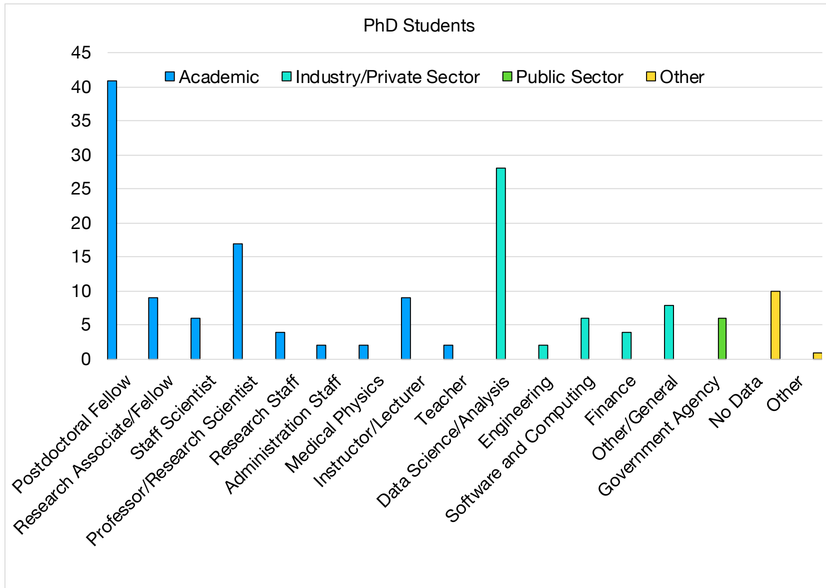

Figure 3: Current positions held by former PhD students that participated in particle physics experimental projects in the last decade.

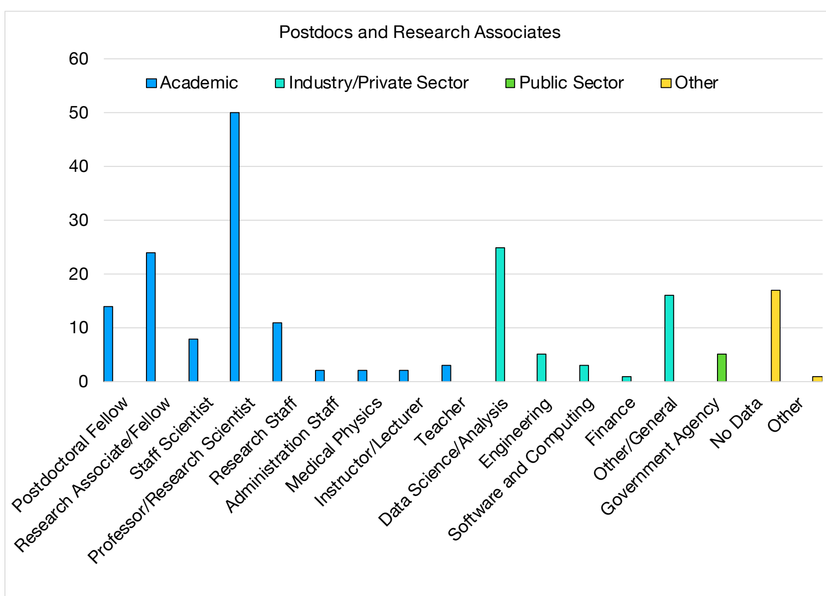

Figure 4: Current positions held by former postdocs and research associates that participated in particle physics experimental projects in the last decade.

9 Program Priorities

Going into the 2022-2026 period, IPP members are contributing to key particle physics projects designed to answer some of the "Big Questions" of our time. The priorities identified by the community are discussed here. The timelines for the various experimental projects were presented in Figure 1, which also lists the scientific questions addressed by each project. There are different ways to consider the project priorities, including the topic breakdown in Figure 1 but also considering strength of the participating group, funding success, and project approval by host lab. The different projects also use very different techniques, ranging from particle colliders running at the "Energy Frontier", high intensity investigations at the "Precision Frontier", neutrino detectors working with particle accelerator beams, large scale detectors investigating cosmically generated neutrinos, and ultra-low-background sensitive detectors investigating rare processes like Dark Matter or neutrinoless double beta decay. The program priorities work in a multidimensional space, ultimately driven by the science.

9.1 Training of Highly Qualified Personnel

One of our key metrics when assessing priorities is the training of students, postdoctoral fellows, and other highly qualified personnel (HQP). The HQP who train in particle physics learn many technical skills ranging from mechanical and electronics design, advanced particle detector construction and operation, leading-edge computing, data analysis including pioneering machine learning techniques, and advanced scientific and mathematical innovations. Our HQP also develop critical skills working in a competitive international environment, collaborating and competing with worldwide experts in many disciplines. Success in this environment requires the development of the kinds of social skills that underpin our success.

While some of our HQP continue in academic research, the majority move into different areas of the private sector. The experience they gain in training in particle physics is unique, and leads to success in other fields and disciplines. The numbers of postdocs and student that members of the IPP community can train is largely limited by the funding available in Discovery and Project grants.

9.2 Theory

Many in the community are addressing the questions by developing theoretical tools and models and it is essential that the IPP theory community continue to be adequately supported from the NSERC subatomic physics envelope. Investment in theory delivers cutting edge science and is also necessary to maximize the scientific output of the experimental program. Canadian particle physics faculty have the capacity to supervise more postdocs and graduate students than their grants permit. This is partly related to the size of the envelope not keeping up with inflation, and partly by the growing community and hires of younger people. When NSERC does receive budget increases for basic science, it is expected that the subatomic physics envelope will increase. It is essential that the theory community Discovery Grants continue to grow with increased funding; in particular, the support for theory HQP seems to have lagged compared to experimentalists over the past few years, and IPP advocates funding to support an increase in the number of theory students and postdocs at a similar rate to the experimental members of the community.

9.3 Current Experimental Program

Among the particle physics experiments in which the IPP community is engaged, there is a group of "essential projects" which will be taking data during this period and in which there has been significant Canadian investment already. In each of these essential projects the Canadian teams have a substantial contingent of fully engaged grant-eligible personnel who are supervising students and who are making important, and in some cases critical, impact on the experiment. Scientific benefits from the investments will be realized during the Long Range Plan period. These are projects that are approved by the host country's funding agencies and labs and span the range of physics being probed by IPP researchers. This group of projects covers the greatest phase-space for discovery in the program. These essential projects also have successful records of HQP training.

In addition to the "essential projects" there are a set of "important projects" that are complementary to the essential projects but which may involve a smaller number of investigators allocating substantial fraction of their research time or which may address a similar discovery goal as an “essential project” but with a more focused discovery phase-space. They are indeed important because there is a potential that they may be the best way of making a major discovery.

9.3.1 Energy Frontier

At the energy frontier, ATLAS is the essential project. ATLAS covers a breadth of physics studies, including the direct search for new TeV-scale particle production, and also precision measurements of the Higgs Boson properties, top-quarks, vector bosons, and other Standard Model particles. Such precision measurements are sensitive to physics at very high energy scales. As the largest subatomic physics project in Canada in terms of numbers of engaged grant-eligible researchers, and with a unique capability to discover BSM physics over a broad physics program, it is essential that ATLAS be adequately supported during this period. Further into the future, the high luminosity LHC (HL-LHC) is a major upgrade that has been approved by CERN. Most of the ATLAS contingent are continuing onto this project and it is an essential future project of the program. ATLAS-Canada has received about $30M from CFI in equipment, labour and infrastructure costs for detector upgrades for the HL-LHC. In addition, Canada has allocated funds to design and build cryogenics modules to house new magnets which will focus the HL-LHC beams and increase the number of proton collisions in ATLAS and CMS; that project will be managed by TRIUMF, working with Canadian industry to produce the modules. The ATLAS-Canada group will continue to require substantial operating funding to exploit these investments into future.

9.3.2 Precision Frontier

Belle II and the TUCAN UCN/nEDM project are the two essential projects at the precision frontier that probe well above the TeV scale in a manner complementary to ATLAS and with teams of Canadian researchers who commit significant fractions of their research time to their respective projects. Considerable investments in infrastructure at TRIUMF for TUCAN have already been made and it is essential that the facility and nEDM experiment operates during this period in order to take full advantage of those investments. Both projects have opportunities to make major breakthroughs and it is essential they receive appropriate levels of operational funding. The ILC is a future precision frontier project that, if funded, would likely attract a large number of Canadian researchers and would require significant resources for a Canadian contribution. The Japanese government is expected to make a funding decision during this Long Range planning cycle. Beyond the timescale of the ILC and the HL-LHC, the Future Circular electron-positron Collider (FCC-ee) is also of interest.

It is also important to support a set of focused precision frontier experiments that have a compelling physics case in terms of their sensitivity to BSM physics and which involve smaller teams and require more modest resources. Moreover, experiments that are currently in the R&D, design or upgrade stages and are awaiting funding decisions with plans to take data in the future should be supported at an appropriate level as their physics goal is to address a “Big Question” in an effective manner.

9.3.3 Neutrino Oscillations

T2K is the IPP flagship experiment measuring the neutrino mixing angles of the PMNS matrix taking data during the 2022-2026 period. T2K is transitioning into the Hyper-K project, with substantially improved sensitivity to measurements of neutrino mixing and possible CP-violation in the neutrino sector. There are a significant number of Canadian researchers allocating a large fraction of their research time to T2K and Hyper-K, and a large investment has been made in this program. Hyper-K will expand the reach of T2K, including the search for proton decay which could indicate new physics at a very high “grand unified” energy scale. With roughly 6 FTE grant eligible researchers involved, this is one of the essential projects of IPP.

The DUNE project is a new effort in Canada, with three faculty members currently committing about 1 FTE ramping to 1.8 FTE over the period of this plan. DUNE is in the R&D phase and will operate on a similar timescale as Hyper-K. The Hyper-K and DUNE experiments will have different beam energies, baselines and detector technologies. These differences in experimental configurations lead to complementary sensitivities to neutrino oscillations, nucleon decay, supernova neutrinos and other physics signatures. DUNE represents an interesting project, which could become an essential one if there is a significant increase in the Canadian faculty commitment.

IceCube is also an essential project that has a broad physics program that includes neutrino oscillation measurements and indirect searches for dark matter particles. It has a modest-sized Canadian team half of whose members commit significant fractions of their research time to the effort. The Canadian IceCube team is also committed to the P-ONE neutrino telescope in the Cascadia basin off the BC coast. P-ONE is still in its R&D phase, but has a strong physics program and, if approved, will be hosted in Canada.

Hyper-K, DUNE, IceCube, Halo-1kT, SNO+ and P-ONE are also sensitive to neutrinos from distant astronomical events, such as supernova explosions which could also be observed in telescopes and gravitational wave detectors. This "multi-messenger" astronomy is an emerging field with strong international interest.

9.3.4 Direct Dark Matter Detection

DEAP, PICO-500 and SuperCDMS are essential projects at SNOLAB searching for dark matter.

DEAP will continue data taking to about 2022, and the group is transitioning to the DarkSide-20k project at the Gran Sasso lab in Italy. There has been significant Canadian capital investment in DEAP and it is crucial that the experiment be supported to ensure that the science from this investment is produced. It is anticipated that the Argon-based dark matter detectors will evolve to the larger ARGO detector, which could be based at SNOLAB, and which could be an essential project to IPP if approved and funded.

PICO-500 has unique, world-leading sensitivity to Dark Matter with interactions that depend on the spin of the recoiling nucleus. PICO has strong Canadian leadership and is a key part of the SNOLAB program.

SuperCDMS expects to begin data taking in 2022. It has a smaller team that is part of a large primarily U.S. funded experiment. The SuperCDMS is sited in one of the SNOLAB Ladder Labs and would stay in that space for the upgrade.

The NEWS-G experiment is an important project taking data during this period where there is very active Canadian involvement with a reasonable, though modest, number of Canadian grant-eligible researchers. The Scintillating Bubble Chamber fits into this important project category as well. There is a strong physics case for each experiment, with the potential to make a dark matter direct-detection discovery.

9.3.5 Neutrinoless Double-beta Decay

The SNO+ experiment at SNOLAB will be operational throughout the Long Range Plan period, and beyond. SNO+ has received substantial capital investment from Canada, and a substantial team allocating a large fraction of their research time to the project. SNO+ has a broad overall physics program, but the most interesting aspect of its program from the perspective of particle physics is its sensitivity to discovering lepton number violation via neutrinoless double-beta decay. It is an essential project.

The nEXO neutrinoless double-beta decay project is in its R&D phase, following from the EXO project at WIPP. Funding from the U.S. is awaiting a final decision. A substantial Canadian group is committed to nEXO, and it is anticipated that it will be located at SNOLAB. If fully approved, nEXO could also be an essential project in Canada.

Another neutrinoless double-beta decay experiment is LEGEND-1000, which is also awaiting a final U.S. funding decision. Currently, the Canadian team on LEGEND is rather small.

9.3.6 Other Projects

The program should also support small, low cost projects with a compelling physics case but which involves a small group of people taking advantage of particular technological opportunities that enable the project and keep the costs low. HALO is an example of such an experiment, and upgrading to the larger HALO-1kT detector at LNGS requires additional resources. MoEDAL is also a targeted experiment with an interesting physics program that is expanding its reach. MATHUSLA is another smaller project with interesting sensitivity to possible long-lived, dark sector particles. VERITAS and NA62 are other examples of such projects; both are in their ramp-down phase during the Long Range Planning period. The level of support for such projects should depend on their scientific reach and the level of efforts by Canadian scientists.

For a balanced program, it is important to ensure that some resources are allocated to smaller projects, especially those in the early stages of development.

9.4 Summary of Particle Physics Priorities Looking Forward

IPP recognizes different funding from different sources, including the NSERC Subatomic Physics envelope, the Canada Foundation for Innovation, direct support from Federal and Provincial governments, and other sources. We split the priorities between NSERC supported and other areas.

9.4.1 NSERC supported areas

- The particle physics community considers the IPP Research Scientist Program to be its highest funding priority from the SAP envelope for particle physics. It has ensured that the field in Canada is functioning at the highest levels in the world and that Canadians are in the highest leadership positions in the international particle physics experiments.
- It is essential to maintain and fully support the subatomic physics Major Resources Support facilities. These community resources, to which there is good and transparent access from across the country, have become increasingly critical to ensuring that the experiments can be designed and built. This is particularly true now as resources at TRIUMF have become extremely stretched because it has ARIEL-II as a top construction priority.
- IPP strongly endorses with high priority the subatomic physics RTI program. It provides modest but critical and timely moderate levels of funding for equipment essential to experiments and R&D initiatives that are often subsequently the basis for substantial CFI requests.
- As the SAP envelope increases, it is essential for the subatomic physics theory community to be secured in maintaining increased operating grants to support increased HQP funding.
- ATLAS is the highest priority project in particle physics in Canada and with the approval of the high luminosity LHC running it will continue to be an essential IPP project.
- Belle II and TUCAN are essential projects at the precision frontier and will take data throughout this Long Range Plan period and beyond.
- T2K and IceCube are essential projects that probe neutrino properties, oscillation, CP violation and mass hierarchy. DUNE, as discussed in Section 9.3.3, is complementary to Hyper-K, but currently has a small Canadian group.
- DEAP, transitioning to DarkSide-20k, is a high-priority program with sensitivity to the direct detection of Dark Matter over a wide mass range, SuperCDMS has high sensitivity at lower masses, and PICO-500 has world-leading sensitivity to Dark Matter if it has interactions that depend on the spin of the target nucleus. All three have committed Canadian teams and are essential projects.
- SNO+ continues to be a high priority neutrinoless double-beta decay experiment. The nEXO neutrinoless double-beta decay project has a large Canadian commitment, but is awaiting funding approval by the U.S.
- As the science develops and new opportunities and ideas arise, it is important to ensure that some resources (at the level of several percent in total) be available to support smaller efforts that are in the early stages of research and development or require limited resources. In all cases, the scientific excellence and significant potential for major scientific advances are the minimal criteria for support.
- The community is waiting for a Japanese decision on the ILC. Should Japan proceed with the ILC, IPP sees this potentially becoming a high priority initiative of our community.
- It is essential to ensure some funds, on the order of \$1M–\$2M per year in total, from the SAP envelope are available for detector and accelerator R&D, including both generic R&D and R&D directed towards specific projects. The future of the field depends on it and R&D provides outstanding HQP training opportunities in skills that are directly transferable to industry. The ongoing R&D programs discussed in this document, such as RD50 and advanced photon detectors, represent such efforts.

9.4.2 Areas with other support

- The CFI MSI program that supports SNOLAB and Compute Canada are absolutely essential for our field to function now.
- The New Digital Research Infrastructure Organization (NDRIO) is a new, national non-for-profit organization that will provide Canadian researchers digital tools, services and infrastructure. Among the NDRIO mandate is a transition of large-scale computing support from Compute Canada to the NDRIO. Particle Physics has pioneered many aspects of advanced, large-scale distributed computing for scientific use, and IPP strongly encourages NDRIO to work with members of our community to ensure that the evolution of Canadian digital research infrastructure meets our needs.
- CANARIE has developed significant network infrastructure that is used by the IPP community. Continued support for CANARIE is absolutely essential for the success of the IPP program.
- The important role of TRIUMF, SNOLAB, and PI for the IPP community cannot be overstated. These institutions have enabled the particle physics community to succeed in the past and will be critical to our future successes.

10 Summary

Canadians have played a key role in the science leading to all three recent particle physics Nobel Prizes. In order to ensure Canada will continue to be a key player in the most impactful particle physics efforts in the future, the NSERC Subatomic Physics envelope will have to ensure that all opportunities for breakthrough discoveries are covered. If minimal increases are not provided, not only will we will lose important, potentially Nobel-level projects, but the number of HQP that can be trained will decrease. This is because the fraction of the envelope that must go into providing technical support, maintenance and non-HQP operating funds, either from project or MRS grants, will continue to increase and funds will have to come from HQP support.

There is a genuine potential for breakthroughs taking place in our field during the period of this Long Range Plan and the Canadian particle physics community is well positioned to be a lead player in those potential discoveries. With a program that spans the energy and precision frontiers as well as the dark matter and neutrino sectors, and is open to new ideas as the science dictates, the IPP is looking forward to producing exciting physics during this period. Given appropriate increases to the SAP envelope, Canada will continue to be playing a key role in particle physics Nobel Prizes in the future.

A APPENDIX: TRIUMF Accelerator Science

25 July 2020 TRIUMF Accelerator Science Submission for the Subatomic Physics Long Range Plan 2022-2026 from O. Kester, A. Gottberg, R. Laxdal, R. Baartman

The Canadian subatomic physics (SAP) community establishes its scientific priorities through five-year Long-Range Plans (LRP). These plans advise the Canadian subatomic physics research community and relevant stakeholders on priorities for both current and future endeavours. Accelerator Science is both a discipline in its own right within modern physics and provides highly powerful tools for discovery and innovation in many other fields of scientific research. Accelerators do support different disciplines of subatomic physics and the Accelerator Science Community does perform R&D to improve operational facilities and prepare technologies for new facilities unveiling new SAP opportunities and unprecedented performance parameters.

Having delivered nearly five decades of discovery, TRIUMF has a vibrant reputation globally as Canada's particle accelerator laboratory and a hub for particle accelerator physics and technology with a wide network of international connections. TRIUMF's accelerator expertise is also recognized for its contributions to major facilities like LHC and the J-PARC neutrino beam. TRIUMF has unique expertise in three areas of Accelerator Science, superconducting radio frequency (SRF), advanced beam dynamics, high-power targets for secondary particle production and remote handling. In view of the LRP, TRIUMF is well positioned to make significant contributions to major international accelerator projects such as the International Linear Collider (ILC), Long-Baseline Neutrino Facility (LBNF), or an Electron-Ion Collider in the U.S. With its growing and world-leading radioisotope beam capabilities at ISAC and ARIEL, TRIUMF has developed into a hub for experimental SAP technology.

The topics addressed in this document are related to the Accelerator Science pillars at TRIUMF and describe the short- and long-term development perspectives of the TRIUMF ACC Science community.

A.1 Nuclear physics related topics

A.1.1 General consideration to increase variety and intensity of secondary beams

Providing intense beams of rare isotope for the nuclear physics community, the development and upgrade of the beam intensity of the 500 MeV cyclotron and the e-linac are key. To support the growths of the various secondary beam programs at TRIUMF, most notably the upcoming additional muon production at BL1A and the radioisotope beam program at the new ARIEL proton line (BL4N) the cyclotron beam intensity must be ramped from the present 300 μA to 400 μA and in the long term to the limits of 500 μA. Developments and infrastructure are required to achieve this goal. This period of the LRP will address upgrades to the H^- source and the injection beam line to improve the beam brightness. Beam studies and new centre region hardware are required to deal with the enhanced space charge. TRIUMF cyclotron tuning studies are limited by the lack of a high-power tuning beam dump so we propose for the long term to design and build a 200 kW-level beam dump in close proximity to the cyclotron that would serve a diverse program for high intensity beam development, studies of materials in extreme radiation fields for the accelerator community, as well as isotope production. BL1A refurbishment will be key for high-intensity operation supporting UCN, CMMS and the emerging actinium-225 isotope production for cancer treatment. For the beam line refurbishment, an improved beam dynamics and beam instrumentation concept will be deployed and for the handling of the highly activated components, modern remote handling technologies like telemanipulations will be applied in the long term.

The TRIUMF e-linac in its present phase providing a 30 MeV, 10 mA electron beam is employing modified 1.3 GHz TESLA type cavities to take advantage of the considerable global design effort at this frequency both for pulsed machines (ILC) but also for cw ERL applications. The goal for the LRP is the ramp-up of beam power on a RIB production targets to 100 kW operation. A future phase will explore the operation beyond that stage, sophisticated machine protection system and high-level application and machine learning to support automatic accelerator tuning.

In the long term, beyond this LRP period, the addition of a second accelerating cryomodule and a ramp-up in beam intensity to the full 50 MeV, 0.5 MW capability is planned. This will harvest the knowledge gain from SRF development in Canada and will provide high performance cavities and will strengthen the core competence on ILC type elliptical cavities in Canada long term. To leave open the possibility of a future ERL ring with injection and extraction between 5-10 MeV, the design of the e-linac employs a single cavity off-line injector cryomodule plus two

2-cavity accelerating modules. The angular off-set between the injector and the main linac allows accommodation of the future ring to drive an FEL for high field THz radiation production.

A.1.2 High-power targets, new target technology and target development

To fully exploit the future increase of beam power provided by the driver accelerators, new high-power target technologies are required. Target development addresses material development and new target station technologies including remote handling. Commissioning of ARIEL target stations and ramping the driver beam power to unprecedented levels is an important objective of this LRP period and will require development projects. The electron-to-gamma convertor target concept that involves a two-stage process where electrons bombard a sophisticated material composite converter positioned in front of the target container to create bremsstrahlung photons need to demonstrate 100 kW capabilities. In the long term a concept will be required to go beyond this power stage, which is a huge challenge.

The TRIUMF targets and Ion Sources Department is embedded in a framework of international collaborations. TRIUMF is leading in the application of high-power targets for radioisotope beam production and handling of target components. New technologies are developed for and with international partners. TRIUMF has an existing strength in the engineering of efficient high-power target material structures. Building on this leading position and within the RADIATE collaboration, TRIUMF is developing the infrastructure and methodology to test materials in extreme GGy/h-level radiation fields and analyze microscopic and mechanical degradation.

RIB ion source and transfer line development capability will be required to provide new, purer, and more intense isotope beams to the NP community. The ARIEL target assembly concept will allow for more versatile and capable ion sources and selective transfer lines. An ARIEL laser ion source will initially be installed in the east station only and will be the element selective work-horse for RIB delivery. In the long term, laser-ionized radioisotopes need to be available from both ARIEL target stations, requiring additional investments.

The development of new targets requires detailed understanding of materials and chemistry at high temperatures. The R&D on new target compositions and materials requires according laboratory infrastructure at TRIUMF, which goes beyond the present stage. Conventional chemistry lab, specialized target assembly and test areas as well as an Actinide target laboratory are mandatory for the long-term future of target R&D for secondary particle production.

A.1.3 ISAC accelerator development perspective

Another focus in terms of beam delivery of rare isotopes to experiments is on the beam preparation and the post acceleration capabilities. In the period of the LRP, TRIUMF ACC division will exploit the full potential of CANREB and the ISAC beam preparation addressing charge state breeders, beam cooler, yield stations and mass separators. In the long term a multi reflection time-of-flight (MR-TOF) analyser will complement the high-resolution separator and the yield stations.

On the ISAC post accelerator side, long term developments even beyond the period of the LRP, are envisaged to boost the final energy of ISAC-II and to add a low energy storage ring for nuclear astrophysics investigations. To boost the ISAC-II energy a stripping foil would be employed at beam energies beyond 6 MeV/u to increase the charge state before a new high performance (high gradient) cryomodule give a boost to >20 MeV/u for A/q=2 ions.

A low energy heavy ion storage ring connected to an ISOL facility provides a unique environment to carry out nuclear physics experiments with stored radioactive beams due to the up to six orders of magnitude increased luminosity compared to "one-time-pass" experiments. The installation of a low-energy storage ring at ISAC-I would create a worldwide unique facility and provide a valuable extension of TRIUMF's physics program by attracting new users. The design of a storage ring and neutron source to generate a neutron target which will allow neutron transfer measurements, is a challenging task, which will provide unique training of young researchers in a new field of Accelerator Science for Canada.

A neutron generator based on (d,d) or (d,t) reactions, the moderation technology and required shielding will lead neutron science and in health physics into a new territory. A suitable storage ring should cover an energy range of about 0.1-10 MeV/u, has approx. 50 m circumference providing a maximum beam rigidity of about 1.5 Tm. A design study will aim for a TDR within the period of the LRP so construction could potentially start their after.

A.1.4 Electron Ion Collider related accelerator technologies

The US decided on the construction of an Electron-Ion Collider (EIC) at Brookhaven National Lab. The EIC is the first major collider to be built in North America in the 21st century and a challenging accelerator project with the most demanding operational parameters in terms of intensity and luminosity for the electron and ion beams. The EIC will require high polarization, sophisticated SRF cavities, hadron beam cooling with intense electron beams that require Energy Recovery Linac (ERL) technologies. The beam dynamics design for the different machines is challenging in particular the spin dynamics and keeping a high degree of polarization of the beams.

TRIUMF's accelerator physicists and engineers could support the construction as a Canadian in-kind contribution. Contributions could be systems like crab cavity cryomodules, high brightness electron gun, beam physics models as well as ERL studies for hadron cooling. The beam physics of the EIC collider accelerators requires handling of high degrees of polarization (up to 85%). The spin dynamics has to be treated within a highly symmetric ring lattice and residual depolarization effects will need correction with partial Siberian snakes. The TRIUMF beam physics group wants to embark on spin dynamics in rings via an involvement in SuperKEKB led UVic. The treatment of spin dynamics in SuperKEKB and associated spin-optics devices will prepare the group for an engagement at the EIC. The goal is to give Canadian scientists a place at the table while engaging senior and junior accelerator scientist in a cutting-edge accelerator project.

A.2 Particle physics related topics

A.2.1 Program on CERN HL-LHC

At CERN's request, Canada has a significant commitment to the HL-LHC's accelerator key hardware for luminosity. Five cryomodules, each containing two superconducting radio-frequency (SRF) dipole cavities, will be delivered to the LHC in the period of the LRP. The RF- dipole cavities, which are the backbone of the powerful accelerator, will be supplied by the DOE funded Accelerator Upgrade Project (AUP) as a U.S. contribution to CERN. The overall cryomodule construction and assembly will be led by TRIUMF, with significant interactions with Canadian industrial contractors.

TRIUMF is also contributing to beam physics studies for the HL-LHC design focusing primarily on investigations of the long-range beam-beam interaction and its influence on beam quality, which in turn affects the maximum achievable luminosity of the collider. Long-term (millions of turns) tracking of protons around the ring at top energy and at collision is performed to scan the dynamic aperture (DA) over a large parameter space. Long -range beam-beam effect compensation / correction with physical wires, running high currents, are considered a valuable option for HL-LHC to increase the DA at small crossing angles either in conjunction with Crab Cavities or as solution to run with a reduced number of crab cavities.

Tests with four wire prototypes in LHC have demonstrated the potential of a wire corrector. The TRIUMF beam physics department does model the wire compensation of the long-range beam-beam effects in the LHC and could show with a Hamiltonian based beam physics model why the compensation of the effects works so well. TRIUMF ACC division does work with CERN on the development of a prototype wire for HL-LHC and Canada via TRIUMF could further develop the design and could provide the final wire correctors for HL-LHC.

A.2.2 Potential contributions to future machines, ILC e.g FCC-ee/FCC-hh

TRIUMF's Superconducting RF group extends the involvement in ILC via the TESLA Technology Collaboration (TTC). Together with UVic, the group already embarked on R&D towards high gradients. Through the utilization of the unique capabilities of TRIUMF's CMMS facility in μ-SR and β-NMR, we are characterizing the magnetic properties of potential new cavity materials, also beyond pure niobium. A better understanding of these fundamental properties has the prospect to develop cavities with much higher acceleration gradients than possible today. Another important aspect is the development of cavity processing techniques like electropolishing or plasma processing for SRF cavities. Those technologies will also significantly enhance the reliability of TRIUMF's existing SRF accelerators.

The Future Circular Collider (FCC) is a long-term goal of a hadron collider spearheaded by CERN with a centre-of-mass energy of the order of 100 TeV in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies. The performance and concept of the hadron collider will follow the LHC R&D with new high field (16 T) superconducting magnets. As a first stage, the tunnel shall house a lepton collider with a centre-of-mass energy of 250 GeV comparable to ILC in the first stage. Main areas for the R&D in the long term, where Canada via TRIUMF could contribute, are in beam physics with analysis of long-range beam-beam effects, wire compensation technologies and the optimization of collimation schemes. In superconducting RF, the crab cavity systems could be explored and prototyped.

A.2.3 Fundamental TRIUMF R&D for neutrino production e.g. Dune, J-Parc

Challenging for the neutrino production are the high intensity primary beam driver accelerators and the high-power target and remote handling systems. TRIUMF Accelerator R&D is well suited to make valuable contributions to target material choices by irradiation studies, providing design for 2-4 MW operation of graphite, beryllium and titanium beam intercepting components and contribution via remote handling technologies of next-generation high-power targetry facilities.

For high power primary beam accelerators in particular for LBNF/DUNE, SRF systems are important. High power driver linacs like PIP-II, will feed beams to several applications, but the separation of bunches delivered by the PIP-II linac to several branches of a facility are required. A deflecting RF-cavity based on an H-mode geometry, developed at TRIUMF, can impart opposing transverse momentum kicks to beam bunch and service several beam paths for high beam power driver machine.

A.3 General Accelerator R&D

A.3.1 Model based and model coupled beam tuning

New accelerator facilities or upgrades of existing accelerators aim for unprecedented beam properties, that do not allow for beam losses and may require smart machine control and protection systems. For the beam production and delivery, sophisticated numerical codes are used to determine operation parameters and to predict beam parameters at locations of beam diagnostics elements. This model coupled beam tuning also provides opportunities to introduce model-based beam tuning and Machine Learning (ML) for particle accelerators.

TRIUMF Accelerator R&D is working on full end-to-end accelerator beam simulation models of accelerators, like the linacs of the ISAC facility. Usually, multiparticle tracking codes are employed, ray tracing thousands to millions of particles through the system depending on the desired accuracy of the calculation. While these provide the advantage of illustrating individual particle evolution throughout the accelerator, they are generally computationally intensive and slow. The TRIUMF developed envelope code TRANSOPTR, a second order beam transport code that is based on the Hamiltonian formalism of relativistic charged particle beams, is capable of a fast output in real time comparable to beam measurement periods. This allows the implementation of the code TRANSOPTR as part of an accelerator tuning tool at TRIUMF as a first step towards model coupled accelerator beam tuning and machine learning. High level applications (HLA) will play a major role in this R&D, on one hand using HLAs such as beam phase space tomography, while on the other hand allowing the development of new application that will allow tests of a model coupled beam tuning procedures.

The objective of this R&D is the training of a tailored NN with a benchmarked TRANSOPTR model to prepare a first test by using a virtual accelerator test-bed platform allowing for off-line testing and analysis of tuning algorithms on the ISAC accelerators. This test-bed is under development in the framework of a Ph.D. thesis. The final long-term goal is the automatic beam tuning of the TRIUMF ISAC linacs and the compensation of drifts of RF-phases of cavities that deteriorate the transmission of beam towards the many experiments served. The transfer of the beam tuning technology to driver beam accelerators like the TRIUMF e-linac will be possible.

A.3.2 Ultra high gradient acceleration – AWAKE

The construction of ever larger and costlier accelerator facilities has its limits, and new technologies will be needed to push the energy frontier. Plasma based wakefield acceleration is a rapidly developing field which is a promising candidate technology for future high-energy accelerators. The AWAKE project at CERN is a plasma wakefield acceleration experiment, driven by the 400 GeV proton beam from the CERN SPS synchrotron, the first of its kind worldwide. Besides demonstrating how protons can be used to generate wakefields, AWAKE will also explore the necessary technologies for long-term.

The efficiency and reach of energy transfer from 400 GeV protons to electrons confer a clear advantage over electron or laser driven alternatives. The AWAKE collaboration formed in 2013 has demonstrated the feasibility with a proof-of-principle experiment and has produced a wealth of results. TRIUMF is member of the collaboration and has identified beam diagnostics for the contribution to the Run 1 experiment and will continue in the period of the LRP to Run 2 the work on sophisticated high band width BPMs, which are essential to guarantee the overlap of proton and electron beam. The collaboration will put TRIUMF accelerator physicists at the fore front of this ground-breaking research.

A.3.3 High intensity proton driver accelerators (medical purpose or neutron production)

TRIUMF's expertise in high power accelerators is requested by the community to support the development of a Canadian Compact Accelerator driven Neutron Source (CANS) and a high gradient high intensity driver accelerator for tumor therapy. CANS technology is modular, highly tuneable, and dramatically less expensive than other methods of neutron production. The R&D for CANS and medical accelerators comprises high current ion sources, high intensity Radio Frequency Quadrupole (RFQ) accelerators and modern high gradient H-type structures and RF-systems. For the neutron production, high power target-moderator systems are a new field of R&D TRUMF's Accelerator division will address in the period of the LRP.

A.4 Accelerator Science education in Canada

The Accelerator Science Community is aware that to drive discovery and innovation, a cohesive and comprehensive training and education is required. Student engagement underpins in many ways the research goals of the accelerator science collaborations worldwide. Universities and Laboratories that employ accelerator technologies will need to develop workforces and train the next generation of researchers, engineers and technicians in the field of particle accelerators as the demand of these qualifications is high.

The number of student research projects in Accelerator Science at TRIUMF is growing and reached now 17 students from different TRIUMF member universities. To grow the program, R&D projects and according infrastructure are required to provide a world class training and hands-on experience with particle accelerators or subsystems. In the last several years TRIUMF has organized an Accelerator Physics and Technology course offered through UBC and the University of Victoria. Between 10 and 20 graduate students register in the course. The lectures and assignment discussions are televised, recorded and offered to students nationwide.

At CLS and the University of Saskatchewan an undergraduate class and research projects for graduate and undergraduate students are offered by the CLS machine director Mark Boland. Boland is Associate Professor at the University of Saskatchewan. Together we plan additional courses for instance at CERN to advertise Canada to international students in Accelerator Science. Moreover, in 2022, TRIUMF and CLS will bring the Joint Accelerator School to Saskatoon.

In the period of the LRP we want to bring together the Accelerator Science community in Canada, as a community of interest to strengthen education and training and to form new national collaborations. The primary aim of a nationwide collaborative community is to provide a platform for contributions to accelerator science research efforts and the development of a future light sources, ion beam technologies, medical accelerators, as well as high energy particle accelerator systems. The long-term vision is a strategic network that will deliver scientific research within the accelerator science field and to the broader user community.

We started the discussion at the CAP congress in 2018 and reached out to organizations that run particle accelerators or will host particle accelerators in the future. We identified the Fedoruk centre, McMaster University, University of Toronto, University of Calgary and University of Montreal as potential members of a national Accelerator Science community. Moreover, we started collaboration with Windsor University on a Compact Accelerator Driven Neutron Sources (CANS) and with the University of Waterloo on an IR-FEL facility located on the Waterloo campus.

A.5 Equity, Diversity and Inclusion Considerations

The broad field of accelerator physics and technology offers great opportunities for a fulfilling career, yet many capable and interested people do not enter in the field. Historically, the Accelerator Science community parallels the predominately "white male" dominated history of physics. While our current lack of diversity in the field is a highly complex issue, without any easy solutions, we can make significant contributions toward developing an inclusive climate, providing effective mentoring and coaching, and addressing implicit bias. There is a need for Equity, Diversity and Inclusion (EDI) to promote underrepresented groups in particular women, persons of colour, persons with disabilities and Indigenous People in Accelerator Science.

TRIUMF and CLS are committed to promoting an inclusive research and training environment and enhancing a strong pipeline for diversity in Accelerator Science. An important element of developing our talent pool in accelerator physics and technology is to eliminate barriers that keep underrepresented groups from entering or later on staying in the field. Actively tailored training plans to each HQP's professional goals, strengths and weaknesses, and personal needs (e.g. family and religion).

Mentoring is broadly understood to be a key component of increasing diversity and improving a climate of inclusion at institutions like TRIUMF, yet most of us have no training in mentorship. To develop role models in the labs to mentors is a long-term vision to address this issue. To create a more inclusive environment, support for childcare via flexible working hours and locations, as well as accommodation of working styles and caregiver responsibilities is envisaged in the period of the LRP. Triggered by the COVID-19 situation, the development of online work and training opportunities is in support of this inclusive environment. Moreover, online technology and automation can support research of persons with limited functional mobility.

Diversity is important in group composition, not only with respect to the four protected groups but also to other dimensions. Concerning recruitment there is the vision in creating a dedicated pool of funding for members of underrepresented groups and advertising scholarship. Also, diversity in the nationality aspect, as Accelerator Science community is global, are taken into account.