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# Institute of Particle Physics Brief to 2017-2021 NSERC Subatomic Physics Long Range Planning Committee

15 October 2015
IPP LRP Brief Preparatory Group[1]

**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. The first core principle of the Canadian Science and Technology strategy, "Moving Forward in Science, Technology and Innovation 2014"[2], is Promoting World-Leading Excellence. The IPP takes great pride in celebrating the awarding of this year's Nobel Prize in Physics to one of our own members, Arthur McDonald, for leading the SNO Collaboration in its discovery of neutrino oscillations. It dramatically demonstrates the excellence of Canadian research in experimental particle physics and reaffirms the important role Canadian particle physicists play on the international scene in addressing the "Big Questions" of our time. Canada's investments in this field pay off with exciting scientific discoveries.[3] Through the IPP, Canada is having a disproportionately high impact on international particle physics projects and the goal of IPP during the period 2017-2021 is to maintain that leadership in the field. This brief documents how IPP plans to do that.

- **The Canadian Particle Physics Landscape**
  The overarching goal of the IPP community is to continue to make significant progress on answering these "Big Questions" of our time:
  - 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 that allows us to exist?
  - How is gravity incorporated into the rest of the particle physics theoretical framework?
  - Is there new physics at or above the TeV scale accessible to the LHC and precision measurements?
  - What is the nature of the neutrino and what can we learn by deeply probing the neutrino oscillation phenomenon?

  In tackling these questions IPP members also train the next generation in multiple and high-level skills at the cutting edge of science, technology and problem solving in an international environment. In order to address these questions experimentally, IPP members have focused their efforts on those projects most likely to generate answers using various techniques and tools in facilities both in Canada and

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[1] The current members of IPP Scientific Council: D. Gingrich (Alberta), T. Grégoire (Carleton), P. Krieger (Toronto), C. Kraus (Laurentian), F. Retiere (TRIUMF), J.M. Roney - Chair (Victoria), B. Vachon (McGill); with the addition of H. Tanaka (IPP/Toronto).

[2] http://www.ic.gc.ca/eic/site/icgc.nsf/eng/07476.html

[3] Another indication of this is that Canada's 2005-2010 average relative citations index, which measures citation rates of a country's researchers in a particular field compared to those in other countries. By this measure of impact, Canada is the top country in the world for our field (Table 4.6 of The State of Science and Technology in Canada, 2012, by The Expert Panel on the State of Science and Technology in Canada.)

around the world. For many of these approaches and experiments, substantial upgrades to improve the sensitivity and likelihood of discovery are planned for operations beyond 2021. Most require funding decisions in 2017-2021 and many require 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 were identified a subset deemed as "essential" to the Canadian particle physics community based on the level of engagement of the researchers in the projects, Canadian investments in those projects to date, and on their potential scientific payoff. These essential projects are:

  - ATLAS, which gives Canada access to the energy frontier;
  - Belle II and UCN/nEDM, two precision frontier experiments which probe above the TeV scale;
  - DEAP-3600 and SuperCDMS which are complementary direct dark matter detection experiments at SNOLAB;
  - EXO and SNO+, two neutrinoless double-beta decay experiments using complementary techniques; and
  - T2K and IceCube, complementary experiments probing neutrino mixing.

  Important projects that will be taking data in the 2017-2021 period and provide breadth to the program are NA62, NEWS and PICO. HALO, a low-cost experiment designed to detect neutrinos from supernovae will also run during this period. VERITAS will be ramping down with a final funding request to be submitted in 2018.

  Important projects in the R&D, conceptual or design stage that will not take data in this period and are awaiting funding decisions are g-2 at J-PARC, Hyper-Kamiokande, ILD/ILC, MOLLER, and PINGU. DEAP-3600 and EXO also serve as R&D projects for DEAP-50T and nEXO, potential next generation dark matter and neutrinoless double-beta decay experiments. There are decision branch-points for these projects that will occur during the period of this Long Range Plan, which are discussed in Section 10 of this brief.

  With the approval of the high luminosity LHC, the ATLAS upgrade for that phase of the experiment is an essential component of the IPP program that requires R&D in the period of the Long Range Plan before commencing construction during this period. The operational support for the existing essential precision frontier experiments beyond 2021 is also required. In addition, other precision frontier projects, if approved in their host country will also require operational support. MOLLER and g-2 at J-PARC, for example, are experiments that have funding decisions expected during this period, though operations will begin after 2021. If funded, the International Linear Collider in Japan will also be at the precision frontier and become an "essential" IPP project requiring resources.

  IPP also deems it to be essential to our program going forward to have one world-leading project in each of these areas:

  - an experiment probing CP violation and/or mass heirarchy in neutrino oscillations;
  - a neutrinoless double-beta decay experiment;
  - a direct DM search experiment.

  Each of these efforts will require considerable resources overall and therefore it is essential that substantial contributions come from foreign partners, including for those projects sited in Canada. Which experiment in each area goes forward will, as with the energy and precision frontier experiments, depend on criteria presented in Section 10 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 the fraction of the envelope (approximately 15%) that has in recent years been allocated to theory Discovery Grants in nuclear and particle physics.

- **NSERC and CFI 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 research and development, as well as to run and 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:

  - R&D requires modest and timely investments in equipment and expertise, funds for which are not available outside the SAP envelope. This highlights the critical importance of the NSERC Research Tools and Instruments (RTI) and Major Resources Support (MRS) programs to our field;
  - the on-going contributions of CFI via its Major Science Initiative (MSI) Fund to the operational support of both SNOLAB and Compute Canada are absolutely essential for our community; and
  - major contributions to particle physics experiments now depend entirely on the CFI Innovation Fund program, 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 therefore of the utmost importance that these funding agencies and other bodies coordinate their work in support of particle physics and avoid making entirely 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: the NSERC Subatomic Physics Long Range Plan should reflect that. 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 SAP 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 HQP’s 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 Nobel Prizes in Physics awarded in particle physics over the past 10 years - 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 2017-2021 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 via the discovery of CP or lepton number violation in the neutrino sector.

# Contents

# 1 Introduction

This document has been prepared in response to the request from NSERC to the Institute of Particle Physics for input from the Canadian particle physics community into the 2017-2021 NSERC 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 2015 Annual General Meeting in June, the IPP organized a town-hall meeting 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 2017-2021 period. Written submissions were then solicited from the presenters and the teams they represented. These submissions and discussions were the input to this document. The first draft of the document was distributed to the IPP membership. A second draft was distributed before holding a virtual town-hall in October in order to solicate feedback in a dynamic forum of the membership. The final draft has taken into account all feedback from the members of the Canadian particle physics community participating in the process.

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?

Through 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 manpower 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 NSERC 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

| | **Fundamental Questions Being Addressed** | | | |
|---|---|---|---|---|
| | Dark Matter/Sector | New Physics >TeV-scale | matter-antimatter asymmetry | Neutrino Properties |
| **Existing IPP Project** | | | | |
| ATLAS | x | x | x | |
| Belle II | x | x | x | |
| DEAP | x | | | |
| EXO | | | x | x |
| IceCube | x | | | x |
| NA62 | | x | | |
| PICO | x | | | |
| SNO+ | | | x | x |
| SuperCDMS | x | | | |
| T2K | | | x | x |
| VERITAS | x | | | |
| **Potential New Projects** | | | | |
| g-2 E34 (J-PARC) | | x | | |
| HALO | | | | x |
| MOLLER | | x | | |
| UCN at TRIUMF | | | x | |
| Hyper-Kamiokande | x | x | x | x |
| NEWS | x | | | |
| ILD/ILC | x | x | x | |

Table 1: Most important fundamental questions in particle physics and which IPP Projects and potential future projects address them.

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 2017 and beyond. Experiments that are not yet IPP Projects are then presented in the next 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. This is followed by a discussion of the roles played by the various funding agencies, labs and the IPP within both the national and international context and comment how these should interact with each other during this period in order to ensure success. We conclude with a summary of the priorities of the IPP community during the 2017-2021 period.

# 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 four general areas of scientific inquiry: inquiries related to dark matter and the dark sector[4], searches for new

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[4] The question of the nature of dark energy that comprises 75% of the matter-energy content of the universe is a question that is in the domain of astrophysics and cosmology rather than particle physics. Nonetheless, some IPP members are intrigued by the fundamental physics problem of dark energy and have a critical impact on that area of research, in addition to addressing

physical phenomena at energies beyond the TeV scale, investigations of the matter-antimatter asymmetry in the universe, and explorations of the nature of the neutrino. Table 1 presents the experiments that are discussed in this document and which of these four 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 Table 1.

Direct searches for the existence of dark matter is carried out by the DEAP, IceCube, PICO, SuperCDMS and VERITAS IPP projects. The DEAP, PICO and SuperCDMS experiments are designed to detect possible interations of dark matter particles within their fiducial volume. 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 and VERITAS 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 from the interaction of known particles. With its ability to carry out precision measurements and search for rare processes, the Belle II experiment 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, Hyper-Kamiokande, and the ILD. The NEWS direct dark matter search experiment will employ gas ionization detectors to achieve unique sensitivity to light dark matter thereby complementing the current IPP program. The Hyper-Kamiokande experiment is expected to have the ability to detect neutrinos possibly originating from the annihilation of dark matter. The ILD sensitivity to physics processes associated to dark matter/dark sector would complement that of the ATLAS and Belle II experiments. 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 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 but have competitive reach to new physics with very different systematic issues. Other potential new IPP projects, sensitive to new physics, discussed in this document include the g-2 experiment at J-PARC (E34), which is at the conceptual stage, MOLLER at JLAB, which is at the design stage, and the International Large Detector (ILD) at the International Linear Collider (ILC) which would take place at a much later date.

The origin of matter-antimatter asymmetry will be investigated by the ATLAS, Belle II and T2K experiments. While both ATLAS and Belle II will provide insights into flavour asymmetry from the study of different processes, the T2K experiment will study the matter-antimatter asymmetries in the neutrino sector. Potential new IPP projects contributing to this line of inquiries include the Ultra-Cold Neutron (UCN) Electric Dipole Moment (EDM) experiment at TRIUMF, which is under construction, Hyper-Kamiokande and the ILD.

Precision particle physics projects that are not yet IPP Projects but which may in the future become so and which are discussed in this document include: The g-2 experimnet at J-PARC (E34), which is at the conceptual stage, MOLLER at JLAB, which is at the design stage, and the Ultra-Cold Neutron (UCN) Electric Dipole Moment (EDM) experiment at TRIUMF, which is under construction. Complementary experiments also addressing precision tests of the SM are also being proposed to CINP including: ALPHAg, FR-APV, Fr-EDM, TRINAT, and Rn-EDM.

Investigations of the nature of the neutrino will be carried out by several different IPP projects. The SNO+ and EXO experiments are designed to search for neutrinoless double-beta decay which would provide direct insights into the nature of the neutrino. 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 and IceCube projects study the nature of neutrino mixing. Their investigations is done using widely different experimental techniques; T2K is an accelerator-based experiment while IceCube is

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the fundamental questions in subatomic physics that we focus on in this document.

designed to study neutrinos from astrophysical sources. In the period of 2017-2021, the complementarity of these two projects should provide sensitivity to both possible scenarios of neutrino mass hierarchies. Canadians are also participating in HALO, a dedicated supernova neutrino detection experiment, and Hyper-Kamiokande, both of which may become new IPP projects in the futur. These two experiments have a distinct scientific program in the study of neutrino properties and use different experimental techniques than the current approved IPP projects.

Potential major future international projects that the community is considering or planning for include the High-Luminosity LHC (HL-LHC) which will require upgrades to the accelerator and the LHC detectors, the Hyper-Kamiokande (HK) and the ILD and the ILC. If funded in Japan, HK and the ILC would be major priority efforts addressing critical issues in the field. HK is discussed in the section on T2K whereas ILD at the ILC is considered in a separate section.

In addition, there are plans for Canadian-based experiments in the future that would potentially require large investments contigent upon whether or not the technology is proven, the science case is still strong, or whether there is a positive decision from foreign funding agencies. An upgrade of DEAP-3600, which is scheduled to start taking data in 2015, to DEAP-50 tonne depends on demonstrating whether or not the single phase LAr technology can achieve ultimate sensitivity and do so in a sufficiently timely manner to ensure that the experiment is competitive. The upgrade of EXO from its current 200 kg mass at the WIPP facility in New Mexico to a 5 tonne nEXO detector is the planned upgrade path for that neutrinoless double beta decay experiment potentially sited in SNOLAB.

At the same time, it is important to keep the door open to new ideas that arise as the science unfolds. For example, a complementary search technique for very light (e.g. $\sim 10$ MeV) dark matter has recently been suggested by a group of theorists from Perimeter Institute. Scattering of galactic dark matter particles with such a low mass falls below the direct detection thresholds. The suggested search mode uses a $\mathcal{O}(100\text{ MeV})$ electron accelerator in conjunction with a large underground detector with negligible backgrounds, such as SNO+. This technique has potential for surpassing in sensitivity all other ways of probing light dark matter. Although this has not moved beyond the “suggestion stage” and investigations into the feasibility of installing an electron accelerator at SNOLAB would be required, it serves to argue that some fraction of the available resources should be available for R&D explorations on new potentially transformative experiments.

Note that other future large projects are also under consideration in the international milieu, such as the Future Circular Collider, but no IPP member has indicated an interest in those efforts nor has submitted a response to the call for briefs in this current Long Range Planning exercise.

From this information it is evident that the community is focused on: searches for evidence of new physics above the TeV scale; searches for dark matter in various ways; measurements of the neutrino mixing angles; searches for matter-antimatter asymmetries 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 questons 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 is 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.

In considering those projects that are not IPP projects but may become so in the future if funded, the community has a long standing expectation that the ILC will be a priority effort. However, the funding for the ILC in Japan not certain. Another scenario is that Japan not fund ILC but goes ahead with funding Hyper-Kamiokande. This would become a priority project for the Canadian community as there is a strong expectation that there would be little difficulty in recruiting people to that project. Of the other non-IPP Projects, there are those that have a reasonable effort assigned to them and those that, should they recruit more members of the community to the effort, can rise in priority.

# 3 Theory

Theoretical particle physicists in Canada work on a very wide range of topics and try to answer all of the "Big Questions" mentioned previously, from the origin of dark matter to the nature of quantum gravity. Theorists propose new models and theories that address issues of the SM, perform computations to predict new phenomena or to obtain precise predictions for the SM. These new theories and predictions will ultimately be confirmed or refuted by experimental observations either in the short or long term. Collaboration between experimentalists and theorists is thus crucial for the progress of the field as a whole. Theorists can suggest new observables and new ways to test models and perform computations that are necessary for the experiments to distinguish signals from background. Conversely, experimental observations will put constraints on the parameter space of proposed models and will also suggest new avenues for theoretical exploration, which in turn might results in proposals for new observations. The recent suggestion by a group of theorists from the Perimeter Institute to look for new light particles using the SNO+ detector in a novel way is a good example of the possible synergy between theory and experiment.

Theorists tend to work in small groups and the projects carried out by theorists have a shorter time scale than typical experiments in particle physics. It is also not rare for theorists to work in a variety of subfields, either over the course of their career or even simultaneously. For example it is frequent for theorists studying BSM physics at colliders to also work on dark matter and make predictions for direct or indirect detection experiments. Similarly, string theorists can apply the tools and ideas of string theory to problems in cosmology, formal field theory or even QCD. Theorists represent roughly a third of the IPP membership, with about 44 members receiving a Discovery Grant from the SAP envelope.

The Perimeter Institute(PI) plays a large role in the Canadian particle theory community with 8 particle physicists who are PI Faculty and 4 who are PI Associate Faculty who are jointly appointed with PI and a partnering university. Those theorists have reduced or no teaching duty, allowing them to devote more time to research. PI also hire a large number of particle physics postdocs. In addition, a large number of theorists across the country have an affiliate status with the Institute, allowing them to visit regularly.

Attending international workshops and conferences is very important for theorists as otherwise they can quickly become isolated. Similarly, it is very beneficial for graduate students to attend a summer school 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.

## 3.1 Research Goals

One of the questions that theorists have been trying to address in the past few decades concerns the mechanism through which the electroweak symmetry is broken. Recently, enormous experimental progress has been made on that front with the discovery of the Higgs boson. Theorists have been very active in proposing ways in which the LHC experiments could test whether or not the newly discovered scalar properties agree with the ones of the SM. So far the agreement is very good, but the measurements are not precise enough to rule out the possibility that the Higgs boson that was discovered is in fact only part of a larger electroweak breaking sector. Again theorists have looked at many possible extensions of the Higgs sector and pointed out ways in which they could differ from a lonely Higgs boson. In fact, the measurements of Higgs boson properties provide new handles that theorist can use to constrain all kinds of BSM physics. Another unresolved question is the so-called naturalness of the electroweak breaking sector. The standard lore is that without new physics close to the weak scale, the Higgs mass can only have its measured value through a very precise cancellation of different terms in Lagrangian, which seems unnatural. There have been many attempts by theorists to come up with natural electroweak symmetry breaking sectors, almost all of which predict new particles which could be observable at the LHC. Examples include supersymmetric models, composite Higgs models and models with extra-dimensions. Theorists build such models, determine how existing experimental data constrain them and predict, with varying degrees of approximation and sophistication, how the models could be tested at existing or planned experiments, either through direct searches or precise measurements of SM processes. In order for experimentalists to be able to distinguish the SM from new physics, they often require precise predictions for SM processes. Providing such predictions is another very important role that theorists play.

The need for BSM physics is clear from two concrete experimental facts: neutrinos have non-zero mass (following from the discovery of neutrino oscillations, for which IPP member Arthur McDonald shared this year's Nobel Prize in Physics with Takaaki Kajita) and the presence of dark matter (DM) in the universe which seems to be required by cosmological and astrophysical observations. Particle theorists have been devoting a lot of attention to the DM issue, both in terms of building models that contain DM candidates, and in terms of computing and predicting signals that DM could leave in different kind of experiments. Indeed, DM could be created and then observed in accelerator-based experiments at $e^+e^-$ or hadron colliders or with a fixed target; by direct detection experiments; and also indirectly via the observation of astrophysical gamma-rays, cosmic rays or neutrinos. In various DM models, the DM is part of a sector containing very light states (the DM itself and/or some mediator) that couple very weakly to the SM. Generically, such very light particles would be difficult to detect at colliders, so other experimental techniques might be better suited for this task. Theorists have been actively exploring how these new light states could be detected at neutrino experiments, meson factories, and beam-dump or fixed target experiments.

Another cosmological observation that points to the existence of new physics is the baryon-antibaryon asymmetry. To explain such an asymmetry (baryogenesis) one needs to invoke CP violation, baryon number violation and out-of-equilibrium phenomena. These conditions make it hard to explain the asymmetry within the SM. This then motivates models of new physics, which might have consequences for Higgs physics and collider physics in general. Furthermore, there are also possible correlations between the baryogenesis mechanism and flavour physics, neutrino physics, dark matter, etc. Computing the baryon asymmetry in a given model is also a difficult task which requires theoretical work.

The SM also has various structures that beg for an explanation which is still lacking. For example, the fermions come in three families that have different masses and mix with each other. In the quark sector the masses are very hierarchical and the mixing angles typically small. In the neutrino sector, some of the mixing angles are large and the hierarchy of masses is unknown. Furthermore, in the neutrino sector the nature (Dirac or Majorana) and the overall scale of the masses is unknown. Once again, theorists have been building new models to explain theses structures. They also examine how new physics in this sector could manifest itself in different experiments such as ATLAS, CMS, LHCb, meson factories such as Belle II and neutrino experiments such as T2K and neutrinoless double-beta decay experiments. They also study the connection between neutrino physics and cosmology.

Theories of particle physics are specified by a quantum field theory Lagrangian. Because very few such theories can be solved exactly, computations are typically performed in perturbation theory, using an expansion in powers of a weak coupling. If no such coupling exists, computations are much harder and many theorists are trying to develop methods to understand the behavior of various quantum field theories without using perturbation theory. This is needed for example to understand QCD (for a wide variety of applications and for understanding some of its properties such as confinement) and to make predictions in various models of BSM physics where symmetries are broken dynamically. It is also needed in astrophysics and cosmology where new techniques to understand gauge field theories at finite temperature, finite chemical potential or with a non-zero $\theta$ term are required.

When no analytical control can be obtained in strongly coupled theories, one can sometimes compute the path integral numerically. This is known as lattice field theory and requires the use of large computer clusters and often involves large collaborations (by theorist standards). A lot of the lattice work is concentrated in computing various quantities in QCD and lattice inputs are most widely used in flavour physics, but they are also very useful, for example, to compute $(g-2)_{\mathrm{muon}}$, rates of dark matter detection, and to determine $\alpha_s$. Beside computational work, lattice field theory also requires more theoretical work to find new ways of putting theories with chiral fermions and supersymmetric theories on the lattice as standard lattice techniques do not work for such theories.

Building a successful and consistent theory of quantum gravity where the the classical theory of General Relativity is extended to obey the principle of quantum mechanics is one of deepest and hardest challenges in physics. In string theory, a successful theory of quantum gravity has been obtained by postulating that the fundamental objects of the theory have a finite extent. String theory is mathematically very sophisticated and is a very rich framework containing many objects such as extra-dimensions, branes, various kind of gauge fields, and of course strings. The study of string theory has led to a large amount of progress, not only for string theory per se, but also in mathematics, in cosmology, in BSM physics and even in the study of QCD.

Many of the ingredients of string theory have been used to build TeV scale field theories with novel properties. For example, extra-dimensions have been used to address to hierarchy problem, the flavour problem, and the AdS/CFT correspondence has shed new light on theories with composite Higgs. String theory also contains many fields which are expected to be lighter than the string scale, such as axion and moduli, and those fields can have consequences for cosmology. In general, the bridge between cosmology and string theory, including models for inflation, aspects of dark energy and dark matter, new scenarios for early universe cosmology, as well as cosmological tests of quantum gravity are topics which theorists have been exploring. Indeed, while in most models the string scale is far too high to be accessible to colliders, string theory or other theories of quantum gravity might leave their imprint in early universe cosmology.

The study of black hole physics is another topic which theorists have been working on in the context of quantum gravity. For example, one of the big success of string theory was the computation, in 1996, of black hole entropy in term of string micro-states. More recently, progress in the understanding of black holes, in particular of the black hole information paradox, has been possible by making use of the AdS/CFT correspondence. The AdS/CFT correspondence is a duality between certain weakly coupled string theories on an anti-de Sitter space (AdS) background and strongly coupled conformal field theories (CFT) in a lower number of dimensions. This duality was one of the most important discovery of string theory in the past 20 years and it has led to an enormous body of theoretical work. Beside black hole physics, it is, for example, also used to study hydrodynamics and has applications for QCD, the quark-gluon plasma such has the one produced at RHIC, and even for condensed matter.

## 3.2 Required resources

In FY2014, the subatomic theorists (including nuclear) received in the form of Discovery Grant about 14% of the overall SAP envelope and increased to approximately 15% for FY2015. Theorists need sufficient funding to hire graduate students and postdocs and to travel to international workshops and conferences. Theorists typically have 1 to 3 graduate students working with them and will often share the cost of one postdoc with a colleague. Indeed, the typical discovery grant is often not enough to support both graduate students and a postdoc and this is a concern, especially for smaller groups that cannot easily share the cost to hire 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 term 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. 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.

In this community, faculty members' capacity to train more students and postdocs is limited solely by funding. Increases to the SAPES envelope, which will result in a corresponding increase to subatomic physics theory Discovery Grants assuming a 15% fraction goes to theory Discovery Grants, will directly increase the number and quality of highly qualified personnel being trained in Canada.

# 4 IPP Projects

## 4.1 The ATLAS Experiment

The ATLAS detector 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 ($\sqrt{s}$) 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 $45\text{pb}^{-1}$, $5\text{fb}^{-1}$ and $20\text{fb}^{-1}$, respectively. Since then, the centre-of-mass has been increased to 13 TeV for Run-2 of the LHC, which began in mid-2015 after a two-year long shutdown (referred to as LS1). ATLAS will continue its data-taking until the end of Run-2 which is scheduled to happen at the end of 2018 after which a long (two-year) shutdown (LS2) is planned. In this period, the Phase-I upgrades to the detector will be made, in preparation for the higher trigger rates anticipated in Run-3, starting in 2021. Phase-II upgrades will take place during a further long shutdown period, LS3, currently planned to start in 2024. The LHC schedule now extends to beyond 2035, with planned luminosity upgrades happening in two Phases along with corresponding, and necessary, detector upgrades.

### 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. In particular, one of the main goals of the LHC experimental program is to elucidate the long-standing issue of the nature of electroweak symmetry breaking. The discovery of the Higgs boson by ATLAS and CMS goes some way towards addressing this goal, but investigations of the properties of this boson continue. Many other questions remain unanswered and could be investigated in the current and 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 fraction of the mass in the universe is in the form of dark matter, with normal baryonic matter accounting only for a small fraction. Dark matter is not accounted for in the SM but it could be produced at the LHC. Furthermore, because of it's versatility, the ATLAS experiment will be able to detect, either directly or indirectly, a large variety of new particles and new forces that might be present beyond the SM .

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 the 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. Measurements of some quantities, such as the Higgs self-coupling, would only be possible with the very large integrated luminosity dataset expected to be collected at the High-Luminosity LHC (HL-LHC) planned to start sometime after 2025. In addition to studying the Higgs and probing the SM 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 that make it an excellent dark matter candidate. Supersymmetry is just one example of the type of BSM physics that will continue to be investigated in future LHC running. Other examples include theories invoking the existence of extra dimensions, theories with composite Higgs and theories with additional gauge sectors (with high-mass gauge bosons sometimes referred to as $W'$ and $Z'$). The LHC is likely to remain at the high-energy frontier for 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 for the future of the field, and it is thus very important to ensure that the detector performance be maintained (or even improved, where feasible) as the LHC luminosity is increased above the original design value.

### 4.1.2 The Canadian team and its impact

The ATLAS Canada collaboration, listed in Table 2, currently comprises 38 NSERC grant-eligible faculty-level investigators, at nine universities (Université de Montréal, McGill, Carleton, Toronto, York, Alberta, SFU, UBC and UVic) and one lab (TRIUMF). These investigators contribute a total of 34.4 FTE to ATLAS, over the current funding period from 2015-2018. There are presently about 130 people in ATLAS Canada, representing about 5% of the ATLAS Collaboration: this includes 26 postdoctoral research associates (RA), 47 PhD students and 18 MSc students. Some of the RAs are based at CERN while others are based at ATLAS Canada institutes. PhD students typically have the opportunity to spend at least a year at CERN, during which time they are expected to spend part of their time contributing to the operation of the detector or to related activities such as data quality monitoring. Not included in the number above are engineers and technical staff who are vital to the continued involvement of ATLAS Canada members in detector R&D and upgrades. In addition, ATLAS Canada typically employs about 25 undergraduates per year. ATLAS Canada members occupy important management and coordination roles in ATLAS, including the role of ATLAS Deputy Spokeperson. In 2015, three of the eighteen Physics Group Convenor positions in ATLAS were occupied by Canadian faculty members. ATLAS Canada members also serve as physics analysis subgroup coordinators, detector upgrade coordinators, and play key roles in detector subsystem operation and management. Two of the six current ATLAS "Run Managers" are ATLAS Canada research associates.

The Canadian group has been involved in ATLAS since 1992 and played a major role in the detector construction, building the hadronic modules of the Forward Calorimeter, two of the four wheels for the Hadronic Endcap Calorimeter, components of the front-end electronics for the LAr calorimeter readout, and all of the signal feedthroughs for the endcap liquid argon cryostats. There were also later contributions, to the High-Level Trigger (HLT), the diamond Beam Conditions Monitor (BCM), the inner tracker, the LUCID luminosity detector, and the MPX detectors used to monitor cavern backgrounds. Most recently, as part of the upgrades done during LS1, a diamond beam telescope was installed, with significant Canadian involvement.

Canada has also been involved in providing distributed computing both for storage and analysis of the ATLAS data. Of the ten globally-distributed ATLAS Tier-1 sites, one is effectively operated and managed by ATLAS Canada and located in Vancouver (initially at TRIUMF and moving to SFU). For large scale simulations and analysis, ATLAS uses close to seventy Tier-2 centres worldwide; four of these centres are provided by Compute Canada shared facilities that are currently located at McGill, SFU, Toronto and Victoria. The support for ATLAS Canada computing now comes from outside the NSERC Subatomic Physics (SAP) funding envelope, with funding for hardware coming from the Canadian Foundation for Innovation (CFI), and from the provinces, via matching funds. The Canadian computing landscape is evolving and the new model for CFI Cyberinfrastructure funding has Compute Canada playing a national role for advanced research computing. As a result, the Toronto Tier-2 site will be moved to a new Compute Canada site in Waterloo and the Tier-1 centre will be moved to a new site at SFU, over the next two years. The Tier-1 operation cannot be discontinued during Run-2, so the facilities at TRIUMF will remain available over the transition period. TRIUMF will remain involved in Tier-1 operations, which are supported in its current 5-year plan, and a service level agreement will be established with Compute Canada.

ATLAS Canada members have been instrumental in operation of the detector, and extraction of scientific results form the ATLAS data, and they will continue to focus their efforts on the upcoming data-taking and on physics studies with the new higher-energy datasets, both in terms of precision measurements of SM properties, and in searches for new physics. Work on R&D and construction for Phase-II upgrades will continue in parallel, with Canadian planned involvement in upgrades to both the inner tracker and the liquid argon calorimeter.

Canadians are also involved in two of the Phase-I upgrade projects: the "New Small Wheel" of the muon system, and improvements to the LAr calorimeter trigger. In each case, the upgrades are motivated by the need to maintain trigger rates within the allocated bandwidth, without increasing the relevant trigger thresholds in a way that would limit the acceptance for interesting physics processes. Once built, these upgrades will be installed and commissioned during LS2 in 2019 and 2020. This will require significant effort from a large part of the ATLAS Canada collaboration. Following LS2, Run-3 anticipates instantaneous luminosities that will reach a level twice that for which the LHC was originally designed. The data sample expected by the end of Run-3 corresponds to the approximately $300\text{fb}^{-1}$ originally envisaged for the full LHC experimental program. However, there is already work in progress aimed at further upgrades to both the LHC and to the associated detectors. The LHC will be upgraded to even higher instantaneous luminosities

| **Investigators** | | **ATLAS Research FTE 2015-16** |
|---|---|---:|
| Justin Albert | Victoria | 50% |
| Jean-Francois Arguin | Montréal | 100% |
| David Axen | UBC | 100% |
| Georges Azuelos | Montréal/TRIUMF | 100% |
| Alain Bellerive | Carleton | 80% |
| François Corriveau | McGill/IPP | 80% |
| Colin Gay | UBC | 100% |
| Dag Gillberg | Carleton | 100% |
| Douglas Gingrich | Alberta/TRIUMF | 100% |
| Richard Keeler | Victoria | 100% |
| Thomas Koffas | Carleton | 100% |
| Robert Kowalewski | Victoria | 80% |
| Peter Krieger | Toronto | 100% |
| Michel Lefebvre | Victoria | 100% |
| Claude Leroy | Montréal | 100% |
| Alison Lister | UBC/CRC | 100% |
| Jean-Pierre Martin | Montréal | 50% |
| Robert McPherson | Victoria/IPP | 100% |
| Roger Moore | Alberta | 75% |
| Dugan O'Neil | SFU | 100% |
| Gerald Oakham | Carleton/TRIUMF | 100% |
| Robert Orr | Toronto | 85% |
| James Pinfold | Alberta | 70% |
| Steven Robertson | McGill/IPP | 50% |
| Pierre Savard | Toronto/TRIUMF | 100% |
| Pekka Sinervo | Toronto | 75% |
| Randy Sobie | Victoria/IPP | 70% |
| Oliver Stelzer-Chilton | TRIUMF | 100% |
| Bernd Stelzer | SFU | 100% |
| Reda Tafirout | TRIUMF | 100% |
| Wendy Taylor | York | 100% |
| Richard Teuscher | Toronto/IPP | 100% |
| Isabel Trigger | TRIUMF | 100% |
| William Trischuk | Toronto | 100% |
| Brigitte Vachon | McGill/CRC | 100% |
| Michel Vetterli | SFU/TRIUMF | 100% |
| Manuella Vincter | Carleton/Killam | 100% |
| Andreas Warburton | McGill | 75% |
| **Total** | | **34.4** |

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

with the goal of collecting about 3ab$^{-1}$ over ten years. The ATLAS detector was not designed to operate at these luminosities, and some parts of the detector will have to be replaced. This will be a significant effort, with the expected upgrade costing close to 50% of the cost of the original detector. Canada will be expected to contribute its fair share to this process if we are to continue as ATLAS collaborators through this period. The main upgrade will be to the central tracker which will not be able to handle the HL-LHC conditions. The plan is to replace the existing inner detector with an all-silicon inner tracker, referred to as the ITk. This represents about half the expected cost of the Phase-II upgrades to ATLAS. The tracker upgrade is essential and will require the participation of a large fraction of ATLAS institutes. Eight ATLAS Canada institutions have expressed interest in contributing, and the Canadian R&D effort for this is already well underway, with a prototype module of the silicon-strip part of the ITk having been successfully built. Another part of the detector that will not function properly at the HL-LHC is the Forward Calorimeter (FCal). The decision on whether or not to replace the existing FCal with a better-suited narrow-gap FCal will be taken by the ATLAS collaboration in June of 2016. The Canadian ATLAS group plans to take part in the construction of a replacement FCal if this option is chosen by the collaboration. If the decision is to not replace the FCal, a small calorimeter (the MiniFCal) might be installed in front of the existing FCal; this would absorb enough of the particle flux in the forward region to allow the existing FCal to operate normally. This solution originated with ATLAS Canada members, and continues to be developed and led by the Canadian community. The ATLAS collaboration is also exploring the option of adding a High-Granularity Timing Detector (HGTD) in the forward region to assist with pileup mitigation strategies in this difficult region. Some Canadians have also expressed interest in these R&D efforts which could develop into a possible Canadian contributions.

### 4.1.3 Required resources

R&D for the Phase-I upgrade projects was funded by two NSERC RTI grants ($410K in 2013 and $575K in 2014) and the construction (now in progress) is funded by a $6.2M CFI grant awarded in 2015. For the Phase-II upgrades, ATLAS Canada has just submitted a significant RTI request (∼ $450K), and it is anticipated that a further RTI request will be submitted in 2016, followed by a CFI request for construction funding. ATLAS has just completed an exercise, with significant Canadian involvement, to define the scope and associated costs of the Phase-II upgrades. This was recently presented to the LHCC at CERN, which will make their recommendation on funding levels in October 2015. The Canadian group expects to contribute of order $10M in equipment costs to the detector upgrades, a figure which excludes infrastructure and labour costs that would also need to be included in a CFI request. Most of the funds requested in the RTI proposal just submitted are for parts, tooling and equipment for construction of 20 ITk silicon-strip modules at each of two proposed Canadian production sites. These funds are vital to ATLAS Canada involvement in the ITk project, since the production of these modules is part of a module assembly site-qualification process that needs to be completed by mid-2017, to meet the ITk construction schedule. It is also vital that CFI cyberinfrastructure continue to provide resources adequate to meet ATLAS needs both in terms of hardware and support.

### 4.1.4 Outlook for the period 2021-2025

The LHC currently has a schedule that extends to around 2035, with periods of operation for physics alternating with long shutdowns for machine improvements and detector upgrades. According to the current schedule, 2021 will see the beginning of Run-3 with the Phase-I upgrades in place, with $\sqrt{s}$ at 14 TeV and twice as much instantanenous luminosity as in Run-2. The ATLAS collaboration will be busy taking data and analyzing the $300\,\text{fb}^{-1}$ of data expected during this Run. They will also be constructing the Phase-II upgrades (LAr calorimeter and ITk) which will require significant manpower and funding. For the ITk component, the silicon-strips module construction will need to be completed in 2021, to meet the schedule for assembling these into the detector and installing it in ATLAS. The upgrades will be installed and commissioned during long shutdown 3 (LS3) in 2024 and 2025. The HL-LHC is expected to operate for at least a decade.

## 4.2 Belle II

Belle II is an experiment to be 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.

Initial (Phase 1) commissioning of SuperKEKB will start in early 2016. The Belle II detector will not be installed, but there will be a variety of specialized detectors to quantify the non-luminosity beam backgrounds. Phase 2 commissioning, starting in mid-2017, will have the goal of reaching a luminosity comparable to that of the original KEKB collider. The Belle II detector, excluding the vertex detectors, will be installed. Phase 3 commissioning, the start of nominal physics running with the full detector, will start in 2018. It will take four years to reach design luminosity, and until 2025 to accumulate the full 50 ab$^{-1}$ dataset.

### 4.2.1 Research goals

The primary physics goal of Belle II is to search for evidence of new physics through a wide range of measurements that are sensitive to the presence of heavy virtual particles, and that can be precisely predicted in the SM . These measurements could include CP violation and other asymmetries, rare decays, or decays that are forbidden in the SM. Belle II will also be sensitive to the direct production of new light particles, including those predicted by dark sector models of dark matter, or additional Higgs particles predicted by Supersymmetric extensions to the SM. In summary, the Belle II research program will directly contribute to the scientific inquiries related to dark matter and the dark sector, searches for new physical phenomena at energies beyond the TeV scale, and investigations of the matter-antimatter asymmetry in the universe.

This program is complementary to the direct search for new physics by ATLAS and CMS at the LHC. If new physics is found there, Belle II observations will help explain its nature by looking for a pattern of deviations from the SM among the many possible measurements. Even if new physics is not observed at the LHC, it is possible for Belle II to see new physics – the mass reach of Belle II through indirect measurements can exceed the LHC direct production limits.

The experiment will also continue the exploration of the weak force and the SM description of CP violation, a program successfully followed by BaBar and Belle. The number of possible measurements can be estimated by the 530 publications produced so far by BaBar.

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. LHCb will be collecting data over the full running period of Belle II.

Areas of specific Canadian interest include direct searches for dark sector particles, possibly starting with phase 2 commissioning; rare B decays using fully-reconstructed B samples; $|V_{ub}|$; and charged lepton flavour violation.

### 4.2.2 The Canadian team and its impact

The Canadian group consists of ten faculty at four universities for a total equivalent of 5.6 FTE (see Table 3). A large fraction of this group were previously members of the BaBar collaboration. The group currently has eleven graduate students (6 MSc and 5 PhD) and as of October 1, 2015, two postdocs work on the project.

For the 2017-2021 period, a slight increase in the faculty FTE count is anticipated and a total of approximately 12 to 14 graduate students are expected to take part in the project, with more PhD than MSc students. The number of postdocs is projected to increase to four by 2017, and then five by 2021. Depending on funding, the group will also have the capacity to supervise 25 undergraduates per year on Belle II projects.

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

| University | Name | FTE |
|---|---|---|
| McGill | Steven Robertson | 0.50 |
| | Andreas Warburton | 0.25 |
| Montreal | Jean-Pierre Martin | 0.40 |
| | Paul Taras | 1.00 |
| UBC | Christopher Hearty | 1.0 |
| | Thomas Mattison | 0.75 |
| | Janis McKenna | 1.0 |
| Victoria | Robert Kowalewski | 0.20 |
| | J. Michael Roney | 0.90 |
| | Randall Sobie | 0.30 |

Table 3: Canadian investigators working on Belle II, with corresponding research FTEs for 2016.

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 10 research associates have contributed to either the Belle II, BaBar or SuperB projects, and a total of 13 PhD theses and 7 MSc theses were granted.

There are 600 collaborators from 23 countries on Belle II, including 360 PhD physicists and 160 graduate students. Currently Canada makes up 2.8% of the PhD physicists and 6.0% of the graduate students.

The main area of Canadian contributions to the Belle II project, at this time, is related to calorimetry, an area that needed personnel when the Canadian team joined the experiment in March 2013. Canadians are in charge of studying the feasibility of upgrading the forward endcap calorimeter – a region with particularly high backgrounds during KEKB operations – from Thallium-doped CsI crystals to pure CsI crystals. Pure CsI has a much faster response time and is therefore less sensitive to backgrounds. However, it does require the use of a new fine-mesh photomultiplier tube, developed by Hamamatsu for the project, and a new preamplifier, developed by the University of Montreal. Projects related to pure CsI include studies of the photomultiplier tube; development of shaping and waveform fitting electronics; radiation hardness studies of CsI and CsI(Tl) crystals; and a beam test to determine timing resolution of CsI and CsI(Tl) crystals under various background conditions. Students are also simulating beam background conditions, and developing detectors for use during the commissioning phases to compare observed and predicted beam background levels, and detectors to provide real-time feedback to accelerator operators during data taking.

Furthermore, the Canadian group has two significant software/operational responsibilities in the calorimeter group: calibration and the GEANT simulation. Calibration will be a multi-year multi-person effort, extending throughout the life of the project. Canada is also responsible for determining the distribution of detector material in simulation and in reality. The Canadian computing effort is focused on the development of cloud computing tools. During the 2017-2021 period, students, postdocs, and faculty will also be producing physics results.

Based on the substantial past Canadian leadership within the BaBar experiment (e.g. spokesperson, physics coordinator, run coordinators, speakers committee chair) and strong presence in many of the most active areas of physics analysis, the Canadian Belle II team is expected to have a significant and visible impact within the Belle II collaboration.

### 4.2.3 Required resources

In the period 2017-2021, the Belle II team does not plan to request funds for any major detector project, in particular, since the physics case for an upgrade to pure CsI crystals is considered insufficient to justify such a project. Consequently, the Belle II Canada team does not foresee any significant demands for technical support from any of the high energy physics MRS.

The projected computing requirements for Canada are based on the team's fraction of the total PhD physicists in the collaboration. This amounts to making 5.8 kHepSPEC available to the collaboration in 2017, increasing to 20.0 kHepSPEC by 2021. For disk space, an estimated 170 TB will need to be made available in 2017, increasing to 1390 TB in 2021. Computing resources allocated by Compute Canada are expected to fulfill the Canadian team needs. These resources are adequate since Belle II uses a distributed computing model for analysis and simulation production.

### 4.2.4 Outlook for the period 2021-2025

Belle II will be collecting and analyzing data through this period. The full data set should be collected by 2025, with analysis continuing for a numbers of years afterwards. The numbers of faculty, postdocs, and graduate students should be stable. One possible upgrade to the experiment during this period would be the installation of equipment to allow polarization on the electron beam. This would enable studies of the weak force via $\gamma - Z$ interference in a manner that is free from hadronic uncertainties. These studies could use a wide range of fermion pair final states produced at SuperKEKB energies: electrons, muons, taus, charm and b-quarks, and would achieve comparable precision to the LEP experiments operating at the $Z$. The Canadian group could be involved by designing and building the polarimeter needed to precisely measure the beam polarization. The cost of such a project would be on the order of \$23M.

## 4.3 DEAP-3600

The DEAP-3600 collaboration is commissioning a 3600kg single-phase liquid-argon detector for direct search of dark matter for operation starting in 2016. Ionizing radiation in liquid argon creates excited $\mathrm{Ar}_2^*$ molecules which decay with the emission of a photon at 128nm wavelength. The detector was designed and constructed with background reduction and maximum light yield as the guiding criteria.

The international collaboration comprises Canada (University of Alberta, Carleton University, Laurentian University, Queen's University, SNOLAB, and TRIUMF); the United Kingdom (Royal Holloway University of London, the Rutherford Appleton Laboratory, and the University of Sussex); and Mexico (Universidad Nacional Autonóma de México).

The DEAP program started with a test detector, DEAP-0, run at Los Alamos National Laboratory. The DEAP-1 7kg prototype detector was designed and constructed at Queen's University and was run at Queen's University and at SNOLAB. The DEAP-3600 detector is under commissioning at SNOLAB in the Cube Hall. A 50-tonne detector is being proposed.

### 4.3.1 Research Goals

The goal of DEAP-3600 is to measure Weakly-Interacting Massive particles (WIMPs) in our galactic neighbourhood. WIMPs are a favoured candidate for dark matter and liquid argon is particularly sensitive for WIMPs with a mass greater than 10GeV and at 100GeV DEAP-3600 will be sensitive to a WIMP-nucleon cross-section of $10^{-46}$ cm$^2$. Effort in design and construction allow for the low backgrounds required for this sensitivity. Materials close to the liquid argon (in particular the acrylic, the wavelength shifter, and the plastic for the neutron-shielding "filler blocks") were specially sourced to ensure low contamination during production. High quantum efficiency photomultiplier tubes (PMTs) were chosen to ensure a high light yield.

There are several classes of backgrounds which must be controlled. Cosmogenic backgrounds are reduced by building the detector underground at SNOLAB and by instrumenting the water shielding around the detector to tag the 2.9 muons/m$^2$/day at SNOLAB. Backgrounds from electromagnetic events such as beta decay from internal $^{39}$Ar are reduced with pulse-shape discrimination (PSD). Electromagnetic events have a low density of energy deposition in the liquid argon. This creates excited argon dimers dominantly in a triplet state which decays in 1.6$\mu$s. Nuclear-recoil events from WIMPs have a high density of energy deposition and create dimers dominantly in the singlet state which decays in nanoseconds. DEAP-1 has shown PSD at the required level of $10^{-10}$ is achievable with $> 50\%$ acceptance with the expected light yield in DEAP-3600.

Neutrons are potentially problematic because they induce a nuclear-recoil signal similar to a WIMP. The largest source of neutrons is the PMT glass. Thus the PMTs are offset by approximately 50 cm from the liquid argon with acrylic light guides or HDPE plastic between the glass and the argon.

| Institution | Name | FTE |
|---|---|---|
| Alberta | Aksel Hallin | 0.5 |
| | Darren Grant | 0.1 |
| Carleton | Mark Boulay | 0.95 |
| | Kevin Graham | 0.2 |
| Queen's | Tony Noble | 0.25 |
| | Mark Chen | 0.05 |
| | Art McDonald | 0.2 |
| | Wolfgang Rau | 0.1 |
| SNOLAB/Laurentian | Bruce Cleveland | 0.3 |
| | Fraser Duncan | 0.5 |
| | Richard Ford | 0.1 |
| | Chris Jillings | 0.7 |
| TRIUMF | Fabrice Retieère | 0.45 |

Table 4: The Canadian investigators working on DEAP-3600 and their research FTEs.

It is possible for radioactive daughters from radon and other sources to plate out on surfaces during construction. These surface backgrounds were mitigated by doing construction in a low-radon atmosphere, by resurfacing the acrylic vessel under vacuum once complete, and by careful preparation of the cooling and argon flow system. Furthermore surface events in the main sphere and on the neck can be reduced in analysis.

### 4.3.2 The Canadian Team and Its Impact

The DEAP collaboration is Canadian led by Director Mark Boulay, a professor at Carleton University. Construction of the detector was led by Mark Boulay and Aksel Hallin. Detector operations (process systems) is led by Queen's University and Carleton University. Operations (data acquisition) is led by the University of Alberta and TRIUMF. Run planning is led by Laurentian University.

The analysis is organized by topic-based working groups. Scientists at Canadian institutions chair the groups responsible for low-level signal processing; PMT calibration; pulse-shape discrimination; event reconstruction; the backgrounds group; run selection, data-quality and live-time; data-flow and software management. (The UK leads the calibration group and Mexico leads on background subtopic.)

The Canadian team on DEAP is listed with their research FTE fractions in Table 4.

### 4.3.3 Required Resources

The DEAP collaboration requires operational support for the science team in order to analyze the data in a timely way. In addition support is required for the detector operations team. Support will include travel to site for calibration campaigns and other operations shifts. Requests have been made to NSERC.

DEAP-3600 has reaped great benefit from engineering, technical, logistical, operational, IT, management, and EH&S support from SNOLAB. During final commissioning and operations DEAP will require continued support. Once in full operation we expect the need for SNOLAB support to be reduced.

The DEAP data set is large ($\simeq 200\,$Tbytes/yr) and analysis is computationally expensive. We have benefited from Compute Canada resources during commissioning to date and will continue to require Compute Canada support.

## 4.4 EXO

The EXO (Enriched Xenon Observatory) collaboration is searching for neutrinoless double beta ($0\nu2\beta$) decay in xenon. It currently operates a 200 kg liquid xenon detector at the WIPP facility in New Mexico and plans to develop a 5 tonne detector, nEXO, at SNOLAB. The search for $0\nu2\beta$ 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.

### 4.4.1 Research Goals

The current EXO-200 detector consists of two back-to-back liquid xenon time projection chambers (TPCs). Energy resolution is critical in $0\nu2\beta$ experiments, as a signal would appear as an excess at the endpoint of the double beta decay ($2\nu2\beta$) energy spectrum, and must be separated from this background process. In EXO, both ionization and scintillation signals are used to measure the energy of candidate events. The primary goal of the experiment is to achieve enough sensitivity to definitively assess a claim for the observation for the $0\nu2\beta$ process. The limits set now by EXO-200 now effectively refute this claim. At the same time, EXO-200 has also investigated the $2\nu2\beta$ process, as limits placed by other experiments suggest that the nuclear wavefunction of xenon may be anomalous. EXO-200 has since made the most accurate measurement of any double-beta decay rate, for this decay, with a limit of $2.165 \pm 0.016(\text{stat.}) \pm 0.59(\text{sys.}) \times 10^{21}$ years. In the coming few years, the collaboration aims to improve the sensitivity of the experiment by a factor of three with upgrade electronics, background control, and analysis improvements.

Following on the success of the current program, EXO collaborators are now aiming for an upgrade to a 5 tonne detector, dubbed nEXO, that will be sited at SNOLAB. The aim of nEXO is to achieve sensitivity to $0\nu2\beta$ arising from neutrinos in the “inverted hierarchy”, where two of the three neutrino eigenstates, separated in mass by the solar neutrino scale, form a quasi-degenerate pair above the other state at low mass. While a wide range of $0\nu2\beta$ rates are possible, if neutrinos are in fact in the inverted hierarchy, there is a lower limit on the $0\nu2\beta$ decay rate assuming that neutrinos are in fact Majorana, and nEXO aims to be sensitive to the full range. With additional background suppression through spectroscopic barium tagging, nEXO will also have sensitivity to a significant range of the $0\nu2\beta$ rates expected in the “normal hierarchy” (*i.e.* the two neutrinos with small splitting below the other) configuration, which can reach below the lower limit for inverted hierarchy all the way to zero.

While nEXO will inherit much of the design of EXO-200, several components do not readily scale to the larger size and new concepts are needed. These include the shielding, which will take the form of a large water vessel and a single-ended TPC, which improves the self-shielding of the detector but puts higher demands on the high voltage system. Pad-based readout is being investigated to replace the wire planes, and silicon photomultipliers with much higher gain and sensitivity may be employed for the scintillation light detection instead of the avalanche photodiodes currently employed. The cryostat may use a carbon fiber vessel rather than copper.

A selection process is under way in the US which will select among the proposed $0\nu2\beta$ experiments and recommend a funding level. This process is expected to converge in 2017. Assuming nEXO is successful, it is expected that the project will follow the Department of Energy’s “Critical Decision” process, with a construction period of approximately five years.

### 4.4.2 The Canadian Team and Impact

Table 5 lists the current faculty and laboratory staff invovled in EXO. For EXO-200, Canadian groups contributed calibration systems, radon control, process system design concepts, veto system mechanical construction, and materials testing through ultra-trace assays. They have been active in the data-taking and analysis process, with K. Graham serving as the first analysis coordinator. J.Farine currently serves as the chair of the EXO-200 collaboration board.

Naturally, Canadians are carrying this leadership into nEXO with K. Graham managing the simulations group, F. Retiere leading the photosensor group, and J. Farine responsible for radon abatement and assay, along with the calibration systems. D. Sinclair and F. Retiere serve on the executive committee, with D. Sinclair also chairing the Collaboration Board. The Canadian team is also leading the development of barium

| Name | Institution | FTE |
|---|---|---|
| J. Farine | Laurentian | 0.9 |
| D. Sinclair | Carleton/TRIUMF | 1.0 |
| K. Graham | Carleton | 0.8 |
| B. Cleveland | Laurentian/SNOLAB | 0.3 |
| U. Wichoski | Laurentian | 0.1 |
| J. Dilling | TRIUMF | 0.05 |
| R. Krücken | TRIUMF | 0.05 |
| F. Retiere | TRIUMF | 0.45 |
| T. Koffas | Carleton | 0.2 |
| R. Gornea | Carleton/TRIUMF | 0.8 |
| T. Brunner | McGill/TRIUMF | 0.6 |

Table 5: Canadian investigators working on EXO, with corresponding research FTEs.

tagging, which will allow background reduction by confirming the presence of the barium ion expected from the $0\nu2\beta$ and $2\nu2\beta$ decays.

Over the past 10 years, the Canadian EXO institutions have graduated 6 MSc students, 1 PhD student, and engaged 7 postdoctoral reserachers. Additionally 44 undergraduates have carried out work for the project. Currently there are 4 MSc and 1 PhD students engaged in the project. With the growing faculty involvement, this contingent is expected to grow.

### 4.4.3 Required resources

The EXO-200 and nEXO effort in Canada have been supported by the NSERC Discovery grant and MRS programs, CFI for research infrastructure at Carleton and Laurentian, and by engineering from TRIUMF and SNOLAB and by the participating institutions.

Looking forward, TRIUMF will continue to play an important role in EXO through the participation of its research scientists, augmented by two new joint faculty members. The project has benefited greatly from V. Strickland, a TRIUMF engineer at Carleton, and further engineering and technical support from TRIUMF, supported by capital funds for the project, will be needed. SNOLAB has supported the project in several ways including critical engineering input to the process design for EXO-200 and conceptual design work for nEXO. The low background counting facilities have also been critical in establishing materials that are suitable for the detector construction. The participation of SNOLAB scientists may increase if the project is hosted at SNOLAB and project issues specifically related to SNOLAB come into play. MRS support at universities has also been important in the conceptual design effort for nEXO, and with construction of detector components expected at universities, their continued engagement will be necessary.

While no rigorous cost estimate for nEXO exists at this stage, one can look to the LZ experiment. The \$70 million cost will need to be supplemented by the cost of enriched xenon, which will be the largest enrichment production ever undertaken by a physics experiment and is estimated to be \$50 million. A CFI and Ontario Research Fund request will be made to realize a capital contribution commensurate with the Canadian contingent on the experiment ($\sim 30\%$). In terms of operational support, given the growth of the effort, the nEXO effort will seek approximately \$1.2 million/year in support through the NSERC Discovery Grant program. Currently, it is not planned to seek capital funds from NSERC.

### 4.4.4 Outlook for the period 2021-2025

By 2021, the currently planned EXO-200 run will have ended, and produced its final results. With critical decisions in the US expected in 2017 and the currently estimated construction time of five years, the nEXO experiment should be operational at SNOLAB during this time period.

## 4.5 IceCube

The IceCube Neutrino Observatory is currently the worlds largest neutrino detector, located near the South Pole Station, in Antarctica. Instrumenting more than a cubic-kilometer of the deep ice as its Cherenkov medium, IceCube, with its low-energy extension DeepCore, is sensitive to neutrinos from approximately 10 GeV to the EeV-scale.

### 4.5.1 Research goals

At the lowest energies, IceCubes DeepCore has opened a window to developing a huge fiducial volume detectors to pursue precision neutrino measurements. These low-energy analyses are now reaching the state where they are limited by systematic effects, and the Canadian groups are leading the efforts to improve the event reconstructions and our knowledge of the backgrounds (e.g. the atmospheric flux) to further refine these measurements over the period covered by the current LRP exercise.

At the highest energies, the IceCube-discovered astrophysical neutrino flux remains statistically limited in the measurements of the neutrino properties, including the spectral shape and the flavour composition (ratio). The latter is one of the primary measurements to test SM physics at extreme energies. Assuming standard neutrino oscillations, the flavour ratio measured at the detector will fall in a narrow range of the full space regardless of the flavour ratio at the neutrino source which is dependent on the properties of each individual source. Any deviation of the measured flavour ratio outside the narrow region implies the presence of BSM physics processes measurable over extremely long astrophysical baselines. An initial flavour ratio has been determined using a joint fit to several of IceCube analyses available to date. Over the next few years, IceCube will continue to analyze the data taken by IceCube in order to reduce the uncertainty on the measured flavour ratio. By specifically designing analyses to study the full set of astrophysical events, and treating their systematic uncertainties in a coherent manner, IceCube will be able to improve on the systematic uncertainty of this measurement. This will allow for precision studies of individual source flavour composition which can be used to study or set constraints on non-SM physics processes such as Lorentz-invariance violation, since such effects typically grow with energy and distance.

### 4.5.2 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 SM searches.

The IceCube project first became a part of the Canadian particle physics community in 2010 with an IceCube institute established at the University of Alberta (UofA). The Canadian IceCube team expanded in 2013 with the addition of a second IceCube institute at the University of Toronto (Clark), also focused on the DeepCore/PINGU physics program. In 2013, the Canadian groups also provided the collaboration computing resources that made possible the analysis resulting in the discovery of a diffuse high energy astrophysical neutrino flux, resulting in a publication in Science (cover November 2013). In 2014, given a growing world-wide interest in the next generation IceCube (IceCube-Gen2) detector, four additional faculty members (Krauss, Kopper - tenure track, Moore and Pinfold) joined the IceCube effort at the UofA. The addition of Kopper, a recognized expert in high energy neutrinos, a leader in the IceCube diffuse neutrino searches and winner of the 2015 IUPAP Young Scientist Prize for Astroparticle Physics, expanded the Canadian program to include expertise in studies of neutrino properties to over nearly 10 orders of magnitude. In 2015, the Canadian program added researchers at Carleton (Armitage) and CNL (Erlandson) with a focus on searching for correlations of IceCube events with space weather. Currently the complete group includes 3.75 FTE Faculty, two postdoctoral fellows, five graduate students (two PhD, three MSc), and five undergraduate researchers. We note the group continues to be identified for leadership roles in the international collaboration. Since 2012 the Canadian IceCube PI (Grant) has been the appointed

| Name | Institution | FTE |
|---|---|---|
| K. Clark | Toronto | 0.75 |
| D. Grant | Alberta | 0.95 |
| C. Kopper | Alberta | 1.0 |
| C. Krauss | Alberta | 0.2 |
| R. Moore | Alberta | 0.25 |
| J. Pinfold | Alberta | 0.1 |

Table 6: Canadian investigators working on IceCube, with corresponding research FTEs.

collaboration's lead scientist for future upgrades in recognition of his role in leading the development of the proposed future low-energy extension called PINGU (the Precision IceCube Next Generation Up-grade). Most recently Grant (new CRC chair, 2014) was appointed as the chair of the publications committee, Kopper as the co-convener for the diffuse neutrino working group, and Clark as co-convener for the both PINGU analysis group and the IceCube oscillations working group. The research FTEs of the team members is in Table 6.

The training of HQP is a core element of the Canadian IceCube program and the group has placed this element at the forefront of its mission goals. To date, the Canadian group has trained a total of three postdoctoral fellows (two active, one currently an INFN fellow), five graduate students (two PhD and three MSc, all on-going) and 14 undergraduate researchers (10 USRAs, two department research fellows).

### 4.5.3 Required resources

The Canadian groups have established expertise in the electronics, calibrations and photosensor development for the second generation optical modules. IceCube anticipates the need for large-scale optical module assembly and test facilities (estimated \$3M via a CFI request in 2017/18). Development of the next generation electronics (mainboards, calibration systems and front end electronics) is estimated to be \$3.5M via a CFI request for activities between 2017-2019, developed jointly at the UofA and TRIUMF. Development of the next generation of photosensors is planned jointly with the UofA, TRIUMF, the UofT, Carleton and York via NSERC RTI and CFI-CRC funds over the full LRP period and is expected to be approximately \$1M. Finally, the group plans to request on the order of 30% of the anticipated Gen2 optical modules in the next CFI Innovation Fund competition. The total anticipated CFI requests from 2017-2021 are approximately \$15M for the project activities.

Computing needs in the LRP period are based on current usage, primarily via the Compute Canada IceCube RAC since 2014, in conjunction with estimated growth of the group to 2021. The current 2015 Compute Canada RAC for the IceCube project is 650 CPU-years, 70 GPU-years, and approximately 120 TB of disk space. Due to the nature of the IceCube simulation and reprocessing jobs, the actual CPU usage ends up being much larger than that allocated. The group disk storage remains rather modest, estimated 25 TB per user for a given analysis set, due to access to the large collaboration disk storage facilities at UW-Madison and DESY to archive the raw event files. In the LRP period under consideration, computing requirements are estimated to reach CPU resources of approximately 4000 CPU-years, GPU resources of nearly 350 GPU-years (made possible by the illume cluster currently proposed as a CFI JELF by Kopper), and disk space of approximately 950 TB.

IceCube anticipates drawing on the engineering and electronics expertise provided by the CPP+ MRS and at TRIUMF in developing the new detector optical modules. At SNOLAB, IceCube anticipates utilizing the space and expertise in low-background counting to develop and characterize the new optical modules.

### 4.5.4 Outlook for the period 2021-2025

The IceCube project is designed to run through 2025 without any modification, permitting the continuation of the current world-leading program to study neutrino oscillations, indirect dark matter searches and properties of high energy neutrinos over that period. However, the newly formed IceCube-Gen2 collaboration, in which the Canadian groups have recognized leadership roles, is now in the planning stages of a full upgrade of the detector arrays both at the high and low neutrino energy thresholds (total project value approximately \$350M). The IceCube-Gen2 detector technology and deployment is very well understood, drawing from the expertise established when constructing IceCube, and the timelines for this part of the project are driven almost entirely by future funding. Assuming an optimistic scenario of project funding in 2017/18, would allow a completion of the PINGU array by 2021 with a $3\sigma$ determination of the neutrino mass ordering and tests of maximal mixing by 2024. Finally, by 2025 IceCube anticipates more than 75% of the high-energy array of the Gen2 will be completed, opening the possibility of pursuing precision BSM tests at the highest energies with the significantly improved statistical sample.

## 4.6 NA62 at CERN

### 4.6.1 Research goals

NA62 is an experiment at CERN designed to study charged kaons decaying in flight. In particular its aim is to measure the $K^+ \to \pi^+\nu\overline{\nu}$ branching ratio with high precision following the pioneering experiments at Brookhaven National Laboratory E787 and E949. NA62 measures many other rare decays with potential access to new physics or that can be used for constraining Chiral pertubation theory. The NA62 is currently running, producing a wealth of data to analyze. The Canadian group is focusing on the analysis of the decay $K^+ \to \pi^+\nu\overline{\nu}$, bringing in its unique expertise, developed as part of the group that measured this decay mode for the first time at Brookhaven. The group is also investigating lepton universality by measuring the ratio of the branching ratios for the decays $K \to e\nu$ and $K \to \mu\nu$, following in the footsteps of the PIENU experiment at TRIUMF that is measuring the same ratio in the pion sector ($\pi \to e\nu$ over $\pi \to \mu\nu$). Contributing to NA62 is thus a compelling extension of the group's analysis effort. The analyses being tackled by the Canadian group focus on observables that can be calculated theoretically with high precision and that are very sensitive to new physics at high mass scales.

### 4.6.2 The Canadian team and its impact

The Canadian group consists of two faculty members at two institutes, for a total of 1 FTE, as shown in Table 7. One student and two research associates are also involved. The group has an excellent track record in HQP training, working on PIENU and other experiments.

The Canadian group is playing an important role in the analysis of the NA62 data bringing their unique expertise acquired in the E787/E949 and PIENU experiments. The group is also investigating the upgrade of the RICH detector, that may be key to achieving optimum sensitivity. The group has a strong track record in designing and overseeing the construction of complex detector systems. With TRIUMF support, the group could make a critical contribution to the design and construction of the new RICH detector.

| **Institute** | **Name** | **FTE** |
|---|---|---|
| UBC | D.Bryman | 0.5 |
| TRIUMF | T.Numao | 0.5 |

Table 7: Canadian investigators working on NA62, with corresponding research FTEs.

### 4.6.3 Required resources

The data taking and data analysis effort requires support from NSERC for manpower and travel, in particular for taking shifts at CERN. The data analysis effort is expected to continue for many years. The detector upgrade is expected to start in 2018 with funding expected to be obtained from CFI or NSERC RTI, depending on the scale. Some technical resources are also requested from TRIUMF to support the R&D and construction effort. The time scale and resources requested are summarized in Table 8. The NA62 data analysis is also expected to require 50 core-years and 50 TB of storage per year, that may be provided by WestGrid.

| **Stage** | **Time scale** | **Operation $** | **Construction $** |
|---|---|---|---|
| Data taking/analysis | 2016-2018 | 200k$/y | 0 |
| Data taking/analysis and RICH upgrade | 2018-2022 | 200k$/y | 1,000k$ |
| Data taking/analysis | 2023+ | 200k$/y | 0 |

Table 8: NA62 project breakdown with resource estimate. The cost of the RICH upgrade is a very rough estimate.

## 4.7 PICO experiment

The PICO collaboration is searching for dark matter using superheated bubble chambers at SNOLAB. In this technology, the target fluid is brought to a metastable superheated state by controlling the temperature and pressure of the fluid. When operating very close to the critical point, the tiniest deposits of energy from dark matter interactions creating a recoil nucleus will induce a rapid phase transition. The emerging proto-bubble is observed with sensitive cameras and the acoustic signal is recorded by piezo-electric transducers. The chamber is then brought to a high pressure which collapses the vapour bubble back into the liquid state, resetting the chamber. The data is then a sequence of photographic images and acoustic traces. As with all dark matter experiments, the control of backgrounds is essential to the success of PICO. The unique design of the PICO detector means that the background mitigation is vastly different when compared with other techniques, a useful discriminator of experimental uncertainties.

The PICO collaboration has currrently 61 members from 17 institutions in 6 Countries: Canada, United States, Mexico, India, Spain and Czech Republic. 86% of the collaboration members come from the 7 institutions in the US or 6 institutions in Canada split 50-50. The Canadian membership currenlty includes 8 faculty members and research scientists (4 FTE), one engineer, 5 postdocs and 12 graduate students. In addition there are typically 6 undergrad students over the summer.

### 4.7.1 Research goals

PICO has the direct detection of dark matter as its primary goal. Electron and gamma interactions in the detector, the bane of most dark matter experiments, can be evaded by tuning the operating parameters of the detector. The measured gamma rejection factor is $10^{10}$ when operating at 3 keV in $C^3F^8$ for example. This is possible as a bubble is only formed when there is sufficient energy located within a small radius, and the low dE/dx in electron/gamma showers does not often permit this to happen. Neutrons are largely mitigated against by going deep underground, and by providing sufficient local neutron shielding for the residuals. However, there is another feature of PICO that makes this background particularly easy to measure. Calibrations with PICO 2L show that roughly 60% of all neutron events created multiple bubbles as the neutrons scattered. If there is a neutron background in the data set, there will need to be a commensurate population of easily identifiable multiples. This will be an even more obvious factor in larger detectors. Free alphas in the bulk material deposit their energy along a track several 10s of micrometers long. This leads to the creation of several proto-bubbles which expand and eventually coalesce into a single observable bubble. In contrast the heavily ionizing recoil tracks from neutrons or dark matter interactions produce a single proto-bubble. The intensity of the acoustic signal depends on the initial acceleration phase of the developing bubble which is vastly different in the two scenarios. We have used this difference to demonstrate an alpha rejection efficiency approaching 100% in the bulk material. The main concern for PICO is the potential to form bubbles from particulates in the fluid. This could be a consequence of alpha radioactivity in the particulates straggling out, or they may cause spontaneous nucleations. The current run of PICO 2L with improved control of particulate generation is showing a much improved performance. A handle on this background would lead the way to developing much larger background free detectors capable of exploring most of the parameter space of interest to PICO. The PICO threshold and choice of fluid enables the experiment to be particularly sensitive at low masses where there have been controversial hints for dark matter signals. By concentrating now on $^{19}$F targets, PICO is particularly sensitive to spin-dependent (SD) interactions, and indeed has the world's best limits in this area. This is the niche area for PICO. The overarching goal of the PICO experiment is to build a sequence of low background detectors with increasing mass and physics sensitivity. With a tonne scale detector, most of the theoretically motivated phase space predicted by SUSY extensions to the standard model will be explored. The discovery potential is large. The program is to complete the current run with PICO 2L and to demonstrate control of the backgrounds. This will be complete by the end of 2015. In parallel, the larger PICO 60 detector is being readied for operations. Engineering runs to test the operation of the modified vessel will commence late 2015, with a physics run to begin in early 2016. This program will likely run for at least a year. In parallel, our understanding of the particulate backgrounds and source has led to a modified (inverted) Right side up design of the chamber. This will be tested operationally in 2016 outside the shielding. By early 2017 the experiment expects to have a good understanding of the PICO 60 chambers in both the conventional and right side up modes, allowing a decision to be made on how to proceed with a larger, more sensitive chambers. This may be in the form of an array of PICO 60 chambers (three sets of the quartz flasks already exist) or a 250 L or larger chamber. In both the latter cases one would need a larger tank for shielding. This would be the activity in 2017 and the following several years.

PICO is quite unique in the world of direct dark matter searches, as it is the only active direct detection experiment focused on fully exploring the spin-dependent interaction phase space. Hence it is also unique in Canada. However, the overall Canadian effort in dark matter is extremely well balanced with different technologies, different targets, and physics capabilities that nicely cover much of the favoured parameter space. There are significant synergies between many experiments in terms of techniques to address the radiological backgrounds, yet the physics they address is sufficiently different that collectively the program is very comprehensive.

### 4.7.2 The Canadian team and its impact

One of the significant advantages of an experiment done on the scale of PICO is that the relatively modest size and quick deployment of new chambers means that the students and postdocs can be heavily engaged in all aspects of the experiment. Students working on PICO participate in the design, construction, commissioning, operation and analysis of the experiment. The students can make real contributions, and gain invaluable experience in hardware and software development, as well as in critical thinking and physics analysis. Although PICO is a relatively small scale experiment, the students and postdocs are exposed to big science by virtue of working deep underground in the SNOLAB facility where there is a rich scientific and technical culture and a mix of projects over a variety of scales. The postdoctoral fellows can grow into positions with significant responsibility. Graduate students are also contributing to all aspects of the experiment and their thesis topics have been very substantial.

Table 9, below, shows the current list of Canadian faculty members along with the fraction of their research time devoted to this project.

### 4.7.3 Required resources

- PICO 2L: This experiment if fully complete and on its final physics run. It may have a future as a test chamber to investigate detector options for larger scale programs, but any modifications required would be rather minor.

- PICO 60: This is also fully funded through an operations grant in the US, and by NSERC in Canada. All the major components are in hand. An upgrade to the water systems, doubling the camera capacity, and a particulate sample/filter system are funded. The new, fully synthetic, quartz vessels have been purchased. No major additional expenses are expected.

- PICO Right Side Up: Most of the money required to operate a test version of this chamber technology outside the shielding is in place. The vessels for this have been purchased with Canadian CFI funding,

| **Institution** | **Name** | **FTE** |
|---|---|---|
| Toronto | Ken Clark | 0.40 |
| Laurentian | Jacques Farine | 0.10 |
| Alberta | Carsten Krauss | 0.50 |
| SNOLAB/Laurentian | Ian Lawson | 0.50 |
| Queen's | Tony Noble | 0.75 |
| Laurentian | Ubi Wichoski | 0.83 |
| IPP/Queen's | Alex Wright | 0.13 |
| Montreal | Viktor Zacek | 0.75 |

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

and many of the ancillary components are in hand. A small RTI may be submitted to NSERC for a contribution to the hydraulic/pressure control system for this new configuration.

- PICO 250 or Array: The experiment plans to apply to CFI for funds to support the Canadian contribution for this next phase of the experiment. The costs will be shared amongst partners. The CFI request is anticipated to be of order 2.5M$ total. The next CFI competition is expected to be announced in 2016 with funds available in 2017. This is well matched to the operational plan.

The computing requirements for the PICO project are rather modest in comparison to other subatomic physics undertakings. Currently all images and piezo traces are digitized and stored, using of order 10 TB. Our expectation is that future runs will have a higher frame speed, more cameras, and some increase in event storage requirements with larger detectors. However, provided the detectors are working, and hence have low backgrounds, the event rate doesnt scale with detector size. A need for several 10s of TB disk space is anticipated. In terms of computing power access to WestGrid or similar will be necessary and a modest usage, of order 20 core-years/year, is expected.

### 4.7.4 Outlook for the period 2021-2025

The comments here are necessarily speculative. If the schedule goes as planned, and the PICO Collaboration has been able to operate a tonne scale detector starting in 2018 or 2019, it will require 2 to 3 years to fully exploit that detector.

There are several possibilities at that stage:

The detector may have worked beautifully with a very low background, but no dark matter will have been detected. At this point we will be at the solar neutrino limit for low mass WIMPs. We could continue to explore the parameter space a bit deeper with longer running and at a threshold above the solar neutrinos, and an evaluation of the physics potential at that time would lead to a decision on the course of action.

If there were no other hints for a dark matter signal, and this area of phase space has been as fully explored as possible, the collaboration would likely seek new directions.

If the detector is performing well, but there is still physics insight to be gained by longer running, and no dark matter has been detected as yet, then we would likely continue to optimize the detector, work on the background issues, and continue operations until the physics reach was exhausted by reaching the neutrino floor.

If there were to be a detection of dark matter (by PICO or another experiment), then verifying the results independently would be important. As a threshold detector we can learn about the particle properties by scanning in threshold. We can also change the target fluid rather easily and operate with a variety of targets to verify a dark matter signal. We can search for low or high mass WIMPs, spin independent or spin dependent, and so would embark on a new mission of validating our claim with new fluids, and learning about some of the dark matter properties in the process (coupling strengths, masses).

## 4.8 SNO+ experiment

The SNO+ experiment is the successor of the successful SNO experiment, located in VALEs Creighton mine in Sudbury Ontario 2 km underground. Much of the original hardware was repurposed, including the acrylic vessel (12 m diameter acrylic sphere with a 7 m long neck for access on top), the Photomultiplier Support Structure (PSUP), the electronics, and the piping and components of the water system.

SNO+ will use liquid organic scintillator (Linear Alkyl-Benzene LAB) with 2 g/L of fluordiphenyloxalzole (PPO) as a target, which has a higher light output and therefore allows access to much lower energy regions compared to the original SNO experiment. As a scintillator detector SNO+ has multiple physics goals: search for neutrino-less double beta decay in Tellurium 130, study of geo- and reactor anti-neutrinos, study of neutrinos from a galactic supernova and solar neutrino studies (pep and CNO cycle), nucleon decay and external background studies during the initial water-fill phase.

The SNO+ collaboration is comprised of over 120 scientists, engineers and students from 22 institutions in Canada, the United States, Great Britain, Portugal, Germany and Mexico. Within Canada, the institutions are: University of Alberta, Laurentian University and SNOLAB, Queen's University and TRIUMF.

### 4.8.1 Research goals

Discovering neutrinoless double beta decay would be a result of great significance in the field, have implications on particle physics and cosmology and contribute to measuring the absolute neutrino mass.

SNO+ is uniquely positioned to attack the $0\nu 2\beta$ question. The construction of SNO+ is nearing completion, once filled with liquid scintillator, SNO+ will have the capability to conduct a tonne-scale double beta decay experiment. This is due to the successful development (by the SNO+ collaboration) of techniques to load large quantities of double beta decaying isotopes into the ultra-low background liquid scintillator. The prime objective of the SNO+ experiment is the search for neutrinoless double beta decay by the addition of the element, tellurium, to the liquid scintillator volume. $^{130}$Te has a high natural abundance of 34.1%, therefore enrichment is not required for an effective double beta decay experiment with tellurium. SNO+ with 0.5% Te, by weight, in 780 tonnes of liquid scintillator would have 1,330 kg of isotope (3.9 tonnes of natTe) in the detector. With a 0.5% Te loading, the collaboration anticipates being able to set a 90% CL half-life limit of $\tau_{1/2} > 1.5 \times 10^{26}$ yr, in 5 years of running, corresponding to a Majorana neutrino mass limit of $m < 51$ meV (using the IBM-2 nuclear matrix elements). SNO+ would extend the sensitivity into the parameter space suggested by the inverted hierarchy.

SNO+ also aims to detect the pep and CNO solar neutrinos. This is still an important goal despite the prioritization of double beta decay in the experiment. The flux of monoenergetic pep solar neutrinos is a fundamental quantity (just like the flux of pp solar neutrinos) and is calculated to 1.5% in the Standard Solar Model (SSM). The pep neutrinos can be detected by looking for the Compton edge in the spectrum from neutrino-electron scattering. With a known source flux and negligible uncertainty in the reaction cross section, a measurement of the rate of pep solar neutrinos has the potential to be a precise measurement of the survival probability at $E_\nu = 1.44$ MeV.

Geo-neutrinos are the electron antineutrinos emitted by natural radioactivity in the Earth. The interest in geo-neutrinos lies in their potential for surveying the deep Earth, thus making a direct measurement of the total amount of U and Th in Earth's crust and mantle. Uranium and thorium radioactivity is thought to account for anywhere from 40% to 100% of Earth's total heat flux (present-day) and direct information coming from detecting the geo-neutrinos from the decay of isotopes in the uranium and thorium chains could pin this down. SNO+ detects antineutrinos using the inverse beta decay reaction: $\nu_e + p \to e^+ + n$. The threshold for this reaction is 1.8 MeV. The positron deposits at least 1.022 MeV of energy because of the annihilation gammas, and thus this reaction is easy to observe in a large, liquid scintillator detector. There is growing interest in the geosciences community in the SNO+ geo-neutrino measurement. The reactor neutrino spectrum observed at SNO+ has a shape with sharp peaks and dips, due to oscillations. The main contributors are the nearby reactors from Bruce Nuclear Generating Station (240 km) and Pickering/Darlington (340 km). The reactor neutrino event rate in SNO+ will be about 90 events/year (oscillated), but the sharp spectral feature enables the fit to extract $\Delta m^2$. Sensitivity projections for SNO+ find that with 3 years of reactor neutrino data, the determination of $\Delta m^2$ equals KamLANDs current measurement uncertainty. The reactor antineutrino results from SNO+ are significant and complementary.

A liquid scintillator detector serves as an excellent supernova neutrino monitor. In the event of a supernova, the detection of the resulting neutrinos using a liquid scintillator gives very good physics capability (as did SNO with heavy water) due to the ability to see charged-current and neutral-current neutrino interactions. In a liquid scintillator, the dominant reaction for detecting supernova neutrinos is the inverse beta decay reaction, a charged-current reaction. SNO+ would continue in SNEWS, the supernova early warning system intended to alert astronomers to the opportunity to observe a new supernova's early light.

For double beta decay, the efforts in SNO+ are complimentary to the efforts in EXO/nEXO - a different isotope is used as well as a different technology. Having both within the Canadian community can only be beneficial. CUORE also uses tellurium as the isotope of choice, but with a very different technology. The proposed sensitivity levels for the upcoming generation of experiments are comparable. BOREXINO and KAMLAND are also liquid scintillator detectors which have published results; SNO+ is larger and deeper and expects therefore to push the precision of the results further. Recent interest in supernova neutrino oscillations comes from the realization that non-linear collective effects occur due to neutrino-neutrino (MSW-like) interactions leading to such phenomena such as flavour swapping. The combination of a NC neutrino-proton scattering measurement by SNO+ of supernova neutrinos with the classic electron antineutrino measurement using inverse beta decay in SNO+, plus a measurement of supernova electron neutrinos (as opposed to antineutrinos) in HALO, could provide evidence for some of these collective phenomena, which are interesting because of their potential sensitivity to the neutrino mass hierarchy.

### 4.8.2 The Canadian team and its impact

As shown in Table 10, a total of 14 Canadian NSERC grant-eligible researchers at 5 different institutions are part of the SNO+ collaboration. There are two additional researchers, 10 Postdocs/RA's, about 18 graduate students, 3 technical people and 3 co-op students steady-state (located at SNOLAB) with additional 6 summer students distributed over the institutions. There are aditional people located at SNOLAB, who are not allocated to a particular institution, such as a project manager, 2 engineers, 3 engineers-in-training, 1 technical assistant and two assay technicians.

| **Institution** | **Name** | **FTE** |
|---|---|---|
| Alberta | Aksel Hallin | 0.5 |
| Alberta | Carsten Krauss | 0.5 |
| Laurentian | Doug Hallman | 0.25 |
| Laurentian | Clarence Virtue | 0.5 |
| Laurentian | Christine Kraus | 0.85 |
| Queen's | Mark Boulay | 0.03 |
| Queen's | Mark Chen | 1.0 |
| Queen's | Ryan Martin | 0.4 |
| Queen's | Art McDonald | 0.5 |
| IPP/Queen's | Alex Wright | 0.87 |
| SNOLAB | Bruce Cleveland | 0.25 |
| SNOLAB | Fraser Duncan | 0.1 |
| SNOLAB | Richard Ford | 0.725 |
| SNOLAB | Chris Jillings | 0.375 |
| All | Total FTE | 7.75 |

Table 10: Canadian investigators working on SNO+, with corresponding research FTEs.

The Canadian groups within SNO+ have major responsibilities for detector components, such as Calibration hardware, Calibration sources, Cover gas, Hold-down ropenet, water system, scintillator systems and isotope purification and loading. The years 2017-2021 will be data-taking period for SNO+ and large number of analyses will be completed, where Canadian graduate students and postdocs will have significant contributions and leadership roles as they have had in the construction and R&D phases of the experiment.

### 4.8.3 Required ressources

SNO+ will take data during the period of the Long Range Plan and will require funds to operate the experiment.

### 4.8.4 Outlook for the period 2021-2025

Recent R&D progress has confirmed that higher loading at the 3-5% Te level is easily achievable (light yield improvements still needed, and are approaching the requirements). Thus, a major goal of the research effort is to demonstrate the concept that SNO+ could be loaded with as much as a few percent Te in the liquid scintillator. SNO+ with 3% Te would correspond to 8 tonnes of $^{130}$Te isotope. The cost of this much tellurium would be approximately $15 million. While this is undoubtedly a large cost, there is no other experimental approach for neutrinoless double beta decay that would be able to effectively scale up to an order 10-tonne scale experiment. The vision for SNO+ as a double beta decay experiment thus goes beyond the initial 0.5% loading. The pace of R&D in the approach to $0\nu2\beta$ has been dramatic – in roughly two years the idea of loading Te has gone from a concept to the point where 5% loadings and higher have been demonstrated. In response to the challenges identified during scaling up the purification of surfactant (for loading tellurium) – a serious obstacle, notwithstanding – SNO+ has developed an alternative tellurium loading technique that does not require surfactant. The new Te-loaded liquid scintillator has transparency that is virtually equivalent to unloaded LAB-PPO scintillator, and is very likely to have superior radiopurity than Te scintillator made with surfactant.

## 4.9 SuperCDMS experiment

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 $\sim$30 kg of Si and Ge detectors, surrounded by a massive shield against environmental radioactivity. The experiment is focusing on the low WIMP mass region.

### 4.9.1 Research goals

SuperCDMS will use two different target materials (Ge and Si) and two different modes of operation in order to optimize the sensitivity in different mass regimes and to have a handle on possible non-standard interactions described by a series of operators in the context of an effective field theory. In the standard operating mode the SuperCDMS detectors have an excellent background rejection capability. In the HV mode a much larger bias voltage is applied leading to a dramatically improved threshold at the cost of background discrimination. The ultimate limitation for direct dark matter search experiments will come from coherent scattering of neutrinos off the target nuclei. For low-mass WIMPs this limitation comes from solar neutrinos. In the 10 GeV range the expectation is to reach the neutrino limit and detect this standard model process for the first time. At lower WIMP masses, down to fractions of a GeV, the experiment expects to achieve a sensitivity roughly one order of magnitude above this neutrino floor. SuperCDMS at SNOLAB will be built with future upgrades in mind that will allow to reach the neutrino floor down to the lowest masses.

There are a number of complementary direct dark matter search experiments pursued at SNOLAB by Canadian and international research groups. SuperCDMS focuses on low-mass WIMPs in the mass range between 0.2 and 10 GeV, using Ge and Si as target for optimum sensitivity over a range of masses as well as some handle on non-standard interactions, which can be identified by comparing rates between different target materials. Complementary approaches are:

- PICO: focus on spin dependent interaction;

- DEAP/MiniClean: focusing on high mass WIMPs, above ∼50 GeV;
- DAMIC (US experiment located at SNOLAB): low-mass WIMPs, similar mass range as SuperCDMS, but not expected to reach the same cross section sensitivity; single target, so no sensitivity to alternate interactions;
- NEWS: reaches even lower masses than SuperCDMS, but presently no expectation that the same cross section sensitivity could be reached. Different target materials for test of alternate interactions.

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 modeling and understanding of backgrounds.

### 4.9.2 The Canadian team and its impact

SuperCDMS is an international collaboration with more than 100 scientists from over 20 institutions. In Canada there are presently groups at Queens University, the University of British Columbia and as of fall 2015 at the University of Toronto. Moving forward, SNOLAB will not only be the host but also a collaboration partner. The operations in Canada are primarily funded by NSERC, but with the addition of Canada Excellence Research Chair Dr. Gilles Gerbier in 2014 who splits his time between this project and the NEWS experiment, there is an additional source of funding in support of specific activities. SuperCDMS presently had four graduate students, one at UBC and three at Queens. One postdoctoral researcher is starting at UBC in fall 2015 and Queens employs one postdoctoral researcher and one research associate (both CERC funded). The focus of the UBC HQP is on the development of the data acquisition system for SuperCDMS at SNOLAB and its implementation for both the experiment itself and the different detector test facilities. The HQP at Queens is concentrating on testing and characterization of detectors and other cryogenic components. In addition to the existing cryogenic test facility the Queens group is developing a new test facility to be located underground at SNOLAB. This CERC funded facility will allow us to perform tests that cannot be performed above ground due to the prevalence of cosmogenic radiation. The CERC funded personnel concentrates on this facility which will also be a gateway for a collaboration with EURECA, a consortium of the European experiments working with cryogenic detectors to search for dark matter. In addition to the above activities the Canadian groups are involved in important aspects of the data analysis. Most recently students at both UBC and Queens made important contributions to the analysis of data taken in the High Voltage mode. Some of this work is a central part of our most recent publication on this subject. Over the past few years the group typically had one or two undergraduate students working with the experiment over the summer, being trained in both hardware work and data analysis. Moving forward, the number of graduate students is expected to average about 10-12 (considering the expected addition of a PI from SNOLAB this would be an average of 1-2 per PI). Plans are to support a total of four postdoctoral researchers (working on DAQ, the test facilities at Queens and SNOLAB, data analysis, and taking a leading role in the operations of the SuperCDMS experiment once it is set up at SNOLAB) as well as one research associate as the project manager for the underground test facility. For installation and operations at SNOLAB, support for one technician is assumed, with some additional technical support by the technical crew from SNOLAB. Additional technical support is expected to be funded by our partners from the US.

### 4.9.3 Required ressources

The total cost for building the experiment at SNOLAB is of order of \$33M US or \$44M Canadian. The funding will come from the US Department of Energy (DOE) and the US National Science Foundation (NSF) with a contribution of \$3.4M (CAD) from CFI and the Province of Ontario. The underground test facility (total budget including personnel ∼\$1.2M) is supported by CERC funds. The initial payload will consist of 30 detectors, but the cryostat has room for a substantially larger number. An upgrade with the final goal to reach the neutrino floor down to WIMP masses of a fraction of a GeV is expected. This upgrade will include improvements to the shielding and the detector design as well as a significant increase in payload.

| Institution | Name | FTE |
|---|---|---|
| Queen's | Phillipe di Stefano | 0.5 |
| Queen's | Gilles Gerbier | 0.4 |
| UBC | Scott Oser | 0.4 |
| Queen's | Wolfgang Rau | 0.9 |
| IPP/Toronto | Hiro Tanaka | 0.2 |

Table 11: Canadian investigators working on SuperCDMS, with corresponding approximate research FTEs for 2016.

Preparations for this upgrade should start in 2019 and the Canadian contribution is expected to be of order of \$2–3M from CFI. The operational funding from NSERC is expected to ramp up over the next few years, reaching a steady state of order of \$0.5M per year in 2018 or 2019.

The bulk of the computing resources for this project are expected to be provided by our US partners. The Canadian groups will set up a small local computing farm at SNOLAB for online data analysis. The use of general computing resources such as HPCVL will be limited. One potential matter of concern (not specific to SuperCDMS) is the limited bandwidth between SNOLAB and the outside world. While this is not yet a limiting factor, it may well become one once the next generation of SNOLAB experiments starts taking data. SuperCDMS receives support from TRIUMF to develop the MIDAS based DAQ system, but the present agreement includes only support that is fully paid for by the US partners. Participation of TRIUMF as a collaboration partner would be highly welcomed. SuperCDMS is presently in negotiations with SNOLAB about the level of support needed for the project. The experiment will draw on SNOLAB expertise in particular with respect to requirements that are specific to the location. This will include an advisory role from SNOLAB for the design and engineering team, but also direct input from the SNOLAB engineering staff. There is also a need for some technical support in particular during the installation of the project. In addition, standard services typically provided by SNOLAB are expected. SNOLAB is planning on joining the SuperCDMS Collaboration. If a collaboration agreement can be reached, an increase of direct support for the project is expected.

SuperCDMS has requested engineering support from the Queens MRS facility for some of the aspects of the underground test facility and installations related to the existing CFI funding. In addition the experiment plans to draw on the MRS for technical support of the operations at Queens as well as the installation of the test facility and the main experiment at SNOLAB.

### 4.9.4 Outlook for the period 2021-2025

As discussed earlier, the SuperCDMS setup is considerably larger than what is required for the initial payload. The goal is to upgrade the experiment with a significant number of advanced detectors, further improving the background and regaining some discrimination at the lowest masses in order to reach the neutrino floor over the full SuperCDMS WIMP mass range of roughly 0.2 to 10 GeV. This requires a moderate upgrade of the facility itself and we expect this funding (see above) to be applied for in 2018 or 2019 with an implementation in 2020 or 2021. If a WIMP signal is observed by any experiment, the upgrade will be tailored for optimum sensitivity to test the observed signal. If the first hints come from SuperCDMS, a larger target mass and lower background will likely be required to confirm the signal and improve the precision. If other experiments first report a signal, then SuperCDMS can contribute to a better understanding by providing a different target material and a different technology. The upgrade requirements in all cases are similar in scope even though somewhat different in the best choice of detector design. The SuperCDMS SNOLAB facility will be installed over the next few years and is expected to yield cutting edge science for at least a decade.

## 4.10 The T2K experiment at JPARC

T2K is a long baseline neutrino oscillation experiment that addresses fundamental particle physics topics in the neutrino sector, such as flavour mixing and CP violation, based on observations of the transmutation of muon neutrinos produced by J-PARC to other neutrino flavours at the Super-Kamiokande (SK) detector located 295 km away. This is large international collaboration with nearly 500 members from 11 nations. It is closely affilliated with the SuperKamiokande project which has 300 members from 12 nations. Some other scientific goals are described below. Canada is a founding member of both T2K and of the recently proposed upgrade of the SK detector, referred to as Hyper-Kamiokande (HK). The critical concept of the use of an off-axis neutrino beam was initially proposed by a Canadian scientist, and implementation of this idea at T2K was likewise spearheaded by a Canadian. Group members play leading roles in the T2K, SK, and HK Collaborations, as well as in the proposed NuPRISM project that will be described further below.

### 4.10.1 Research goals

T2K is at the forefront of the world neutrino oscillation program. It has made ground-breaking discoveries (observation of $\nu_e$ appearance) and the most precise measurements of fundamental parameters such as $\theta_{23}$ and $\Delta m^2_{32}$ (via $\nu_\mu$ disappearance), and leads the search for CP violation in the neutrino sector, through the combined measurements of neutrino and antineutrino oscillations. This program confronts critical questions regarding our understanding of the Standard Model, including the origin of neutrino masses and mixing parameters, while also providing important input to our understanding of our universe. These advances have propelled a worldwide program which will be the focus of future US particle physics efforts at Fermilab (LBNF/DUNE) and the Japanese program (J-PARC/HK), with significant participation and contributions from Europe and CERN. Even as these future plans come together, it is clear that T2K will be at the frontier for at least another decade before these new experiments start operations around 2025.

Since their initial results, a few years ago, T2K has moved forward with this program, first with a joint analysis of the $\nu_\mu$ disappearance and $\nu_e$ appearance channels that has disfavoured a large fraction of possible values of the CP-violating phase $\delta_{\mathrm{CP}}$. As of this time, T2K has also accumulated its first significant exposure with the beam in antineutrino mode, producing competitive measurements of the $\bar{\nu}_\mu$ disappearance and the first $\bar{\nu}_e$ appearance results. Within the next year, a first joint analysis of all four modes is planned, which will constrain all the relevant oscillation parameters within a consistent framework and achieve maximum sensitivity.

In addition to the existing program, T2K collaborators in Canada are developing the future program, via participation in the HK project, a proposal to upgrade the SK detector to a volume 25 times larger. Such a detector would allow a decisive observation of CP violation in neutrino oscillations, across a large fraction of possible values of $\delta_{\mathrm{CP}}$, while increasing the sensitivity to proton decay by an order of magnitude. It would also serve as an observatory for astrophysical neutrino sources such as dark matter annihilation, supernovae, etc. The project is in its R&D phase with a formal funding request to the Japanese government expected in 2017, with a scheduled operational start in 2025. Canadian activity in this effort is focused on photosensor and readout electronics R&D and development of the overall physics program.

Canadian T2K members are also leading the NuPRISM proposal to exploit the variation of the neutrino energy spectrum from the T2K off-axis neutrino beam, by constructing a large water Cherenkov detector $\sim$1 km away from the source, that spans a large range of off-axis angles. The variation of the energy spectrum across the detector can be used to effectively simulate the neutrino interactions that would arise from a narrow band of neutrino energy. This allows a key systematic uncertainty, namely the relation between the outgoing lepton kinematics and the incoming neutrino energy, which is sensitive to the details of nuclear modelling, to be directly confronted and reduced. Similar techniques will also allow a measurement of the $\nu_e/\nu_\mu$ cross-section ratio as a function of neutrino energy, another important source of uncertainty for precision neutrino oscillation measurements, to be constrained.

The T2K and HK projects have significant synergy and complementarity with other neutrino experiments in Canada. They are the only long-baseline efforts in Canada, and are expected to be at the forefront of the effort to observe leptonic CP violation. SK and HK likewise maintain a unique sensitivity for proton decay. IceCube has published its first study of neutrino oscillations using atmospheric neutrinos. With additional running, and the PINGU upgrade, that program can be expected to produce competitive measurements of $\theta_{23}$ using complementary methods, while having better sensitivity to the neutrino mass hierarchy. The neutrino astrophysics programs of the experiments are also highly complementary, with SK and HK providing the best sensitivity at sub-GeV energies with IceCube/PINGU aiming at higher energies up to the PeV range. In planning for these future efforts, strong synergies were identified in the detector hardware requirements for PINGU and HK. A cooperative and coordinated short-term R&D program has begun, to develop photosensors, readout electronics, and calibration devices for both programs during 2016–2017. As PINGU and HK remain unfunded at this point, funding decisions for both projects in their host countries will determine future effort. The excitement in neutrino physics remains high and should HK not be funded, there may be a migration by Canadian researchers in the Fermilab Long Baseline Neutrino Facility which hosts the DUNE experiment.

### 4.10.2 The Canadian team and its impact

As shown in Table 12 the Canadian ITk group comprises 17 grant-eligible researchers (12.6 FTE) including faculty at universities across the country as well as scientific staff at TRIUMF, some with adjuct faculty appointments. In addition, Mark Hartz, who holds a joint TRIUMF/Kavli-IPMU research scientist position focused on T2K/NuPrism/HK in Japan may return to work permanently as a grant-eligible Research Scientist with the Canadian group in the next few years. The Canadian T2K group currently has six postdoctoral research associates, eleven graduate students and several undergraduates. Six PhD and six MSc degrees have been awarded, and six past postdoctoral group members have moved to faculty or staff positions in Canada or the US, with all of them continuing to play leading roles in T2K.

| **University** | **Name** | **FTE** |
|---|---|---|
| Regina | M. Barbi | 0.7 |
| York | S.Bhadra | 1.0 |
| TRIUMF | R. Helmer | 0.3 |
| Winnipeg | B. Jamieson | 0.5 |
| Victoria/TRIUMF | D. Karlen | 0.8 |
| Alberta | P. Kitching | 1.0 |
| TRIUMF | A. Konaka | 0.6 |
| IPP/Toronto | J. Martin | 1.0 |
| TRIUMF/Winnipeg | T. Lindner | 1.0 |
| Regina | E. Mathie | 1.0 |
| UBC | S. Oser | 0.6 |
| TRIUMF | J.-M. Poutissou | 1.0 |
| TRIUMF | R. Poutissou | 1.0 |
| TRIUMF | F. Retiere | 0.1 |
| TRIUMF/Regina | R. Tacik | 1.0 |
| IPP/Toronto | H. Tanaka | 0.7 |
| TRIUMF | S. Yen | 0.3 |

Table 12: Canadian investigators working on T2K, with corresponding approximate research FTEs for 2016.

The group was responsible for the design and construction of an optical transition radiation (OTR) beam monitor that plays a critical role in the neutrino beamline operation, as well as for the fine-grained scintillating detectors (FGDs) and time projection chambers (TPC) that form the core of the T2K near detector (ND280), where neutrino interactions are studied prior to oscillation effects, in order to constrain the large systematic uncertainties due to the neutrino flux and interaction cross-section.

The group has been active in developing the neutrino-flux prediction, and aims to reduce the dominant hadronic modelling uncertainties by improving the treatment of pion interactions and incorporating the NA61 replica target measurements. There are also large uncertainties in extrapolating the near detector measurements of neutrino-carbon interactions to the expected interactions on water at SK. Canadian members are now working with the FGD2 water target data to reduce this uncertainty. Using new reconstruction tools developed at SK, they are also developing a selection for neutrino interactions with pion production, a class of events currently treated as background and removed by the selection cuts. By explicitly reconstructing these interactions, it is hoped to increase the effective statistics at the far detector and improve the ultimate sensitivity of the experiment. Members of the group have led various T2K analysis efforts, including those resulting in the recent measurements of $\theta_{23}$ and the constraints on $\delta_{\mathrm{CP}}$.

The Canadian group also provides "Tier-1" storage for T2K data, at TRIUMF, and about half of the collaboration's computing resources. T2K currently uses 610 core-years of computing on Compute Canada resources (primarily Scinet and Westgrid). This is expected to grow as T2K statistics and the necessary simulation sample sizes grow.

Canadian T2K members sit on the collaboration's executive board, and fill (or have filled) other leadership positions such as Run Coordinator, Analysis Coordinator and Publications Committee Chair, amongst others. Canadian members also sit on the international Steering Committee for the HK project, and lead the electronics and DAQ development.

### 4.10.3 Required resources

The group expects to continue operation and maintenance of the Canadian T2K detector contributions to T2K (OTR, FGD, TPC, ND280 network, slow control and services) during 2017-2021. Resources are currently required mainly for the newly initiated HK and NuPRISM projects. A joint NSERC RTI request is being submitted in 2015 with Canadian PINGU collaborators for development of the multi-Digital Optical Module (mDOM) concept for both experiments. The mDOM consists of a large glass or acrylic pressure vessel in which an array of 3" photosensors and related electronics and calibration devices are enclosed to protect against the pressure of the ice and/or water. The R&D will involve testing and characterizing 3" PMTs from different vendors, designing and testing light collectors and a mechanical matrix to support the various components, and readout electronics. For HK, they plan to develop a veto system, likely based on relatively large photosensors ($>5$") with light collection through wavelength shifters. Development of photosensor electronics based on full waveform digitization has been in development for a few years; it is expected that this will continue with a particular aim towards optimizing to the mDOM design. Through the TRIUMF-based Photosensor Test Facility, they will continue testing and study of large area photosensors, including the 20" PMT used in SK, new prototype devices using a "box and line" dynode design, and hybrid photosensors using silicon-based amplification. The goal of the work proposed in the RTI is to explore the various options, optimize the design, and build prototypes. The application of the mDOM concept to NuPRISM, also a large water Cherenkov detector, will be explored. In the event of approval of either NuPRISM or HK (expected in 2017), CFI funds would be requested for contributions to photosensor and electronics for the experiment.

### 4.10.4 Outlook for the period 2021-2025

In the period from 2021-2025, the current T2K program is expected to be in its final stages, and approaching its ultimate exposure and sensitivity. If the HK project is approved, the construction of the experiment would be underway, with the start of operations planned for sometime shortly after 2025. This would open a new era of highly sensitive and precise measurements of CP violation in neutrino oscillations and of searches for proton decay. If the NuPRISM project is approved, operation of the detector should start during this period, and contribute to reducing the systematic uncertainties in the ultimate T2K analyses, while laying the ground work for near-detector studies for HK.

## 4.11 VERITAS

VERITAS is an array of four 12-metre imaging atmospheric Cherenkov telescopes located in southern Arizona. It is one of three such detectors world-wide and is sensitive to gamma-rays with energies in excess of

100 GeV. It has been in operation since 2007 and has detected 45 astrophysical sources; half of these were discoveries and half were confirmations. The collaboration comprises approximately 100 scientists, including students, from Canada, Germany, Ireland, and the USA.

The McGill group is currently the largest in the collaboration and consists of two faculty members (D.Hanna and K. Ragan), two post-doctoral researchers, and five graduate students. The group supplied components to build the telescopes and has developed a number of devices to provide precise calibrations. Its scientific focus is primarily on topics in particle astrophysics such as indirect detection of dark matter, tests of Lorentz invariance, and searches for evaporation of primordial black holes. Over the last ten years the McGill gamma-ray group has had ten postdocs and graduated seven Phd students and four MSc students. Nine summer students have been part of the group.

VERITAS will run until June 2019. It will be succeeded by the Cherenkov Telescope Array (CTA) which is currently in the final design stages. The McGill group will not be part of the CTA consortium but will remain involved with VERITAS until all the graduate students finish their theses. The group is submitting an application to NSERC for a project grant which will last until April 2019. Constant funding is requested for this period. A final project grant request incorporating a ramp-down will be submitted in the fall of 2018.

VERITAS is a mature detector. There are no anticipated needs for new equipment or technical support. Computing can be handled with in-house resources and there are no direct relationships with other Canadian SAP activities.

# 5 Other Projects

## 5.1 The g-2 experiment at J-PARC (E34)

### 5.1.1 Research goals

The g-2 E34 experiment at J-PARC is proposing to improve upon the measurement performed by the BNL E821 showing a $3.6\sigma$ discrepancy between the measured anomalous moment of the muon and the standard model expectation. It is proposing a very different technique than BNL E821 relying on a cold muon beam produced by laser dissociation of muonium in vacuum, which can then be maintained in a storage ring without requiring any electric field. The goal of the experiment is to achieve a sensitivity comparable to BNL E821 by 2020 but with very different systematic errors followed by an upgrade to achieve optimum sensitivity. The Fermilab E989 experiment is expected to improve the precision of the E821 experiment using the same technique around the same time. So far, the Canadian group focus has been on developing a solution for producing muonium in vacuum with a reasonable efficiency in collaboration with Japanese collaborators. The production yield of muonium in vacuum that has been recently achieved at TRIUMF is sufficient to meet the intermediate sensitivity goal (E821 sensitivity).

### 5.1.2 The Canadian team and its impact

The list of Canadian faculty involved in the project is shown in Table 13. It is a small team of world leading experts in muon physics who have played a key role in developing the muonium in vacuum production technique. The J-PARC g-2 collaboration is currently being formed and responsibilities for the project have not been defined yet. The current focus of the group is on designing a monitor of the muon beam polarization.

The Canadian group is planning to hire a graduate student to work on the project during the design and construction phase and up to two students during the analysis stage.

### 5.1.3 Required resources

The Canadian contribution will be fairly modest as shown in Table 14. Resources are expected to be obtained from NSERC and TRIUMF is expected to provide technical support. Computing requirements are expected to be modest.

| **Institute** | **Name** | **FTE** |
|---|---|---|
| UVic emeritus | G. Beer | 0.15 |
| UBC emeritus | J. Brewer | 0.15 |
| TRIUMF | Glen Marshall | 1.0 |
| TRIUMF emeritus | Art Olin | 0.2 |

Table 13: Canadian investigators working on the J-PARC g-2 experiment, with corresponding research FTEs.

| **Stage** | **Time scale** | **Operation (k\$/y)** | **Construction (k\$)** |
|---|---|---|---|
| Design | 2015-2017 | 50 | 0 |
| Construction stage 1 | 2018-2019 | 100 | 100 |
| Data taking stage 1 | 2019-2021 | 100 | 0 |
| Construction stage 2 | 2021-2023 | 100 | 100 |

Table 14: g-2 at J-PARC Project breakdown with resource estimate. The cost estimates are approximate.

## 5.2 MOLLER

### 5.2.1 Research goals

The MOLLER (Measurement Of a Lepton-Lepton Electroweak Reaction) experiment will make a high precision measurement of the parity-violating asymmetry (APV) in the scattering of longitudinally polarized electrons off unpolarized electrons, using the upgraded 11 GeV beam in Hall A at Jefferson Laboratory. The SM prediction for APV for the MOLLER design is ∼35 parts per billion (ppb) and the goal of the experiment is to measure this quantity with a statistical precision of 0.73 ppb, constituting an overall fractional accuracy of 2.1%. Polarized electron scattering off unpolarized targets provides a clean window to study weak neutral current interactions that can be calculated accurately with a very low uncertainty in QCD predictions.

### 5.2.2 The Canadian team and its impact

The Canadian group consists of 11 faculty at five universities for a total equivalent of 2.2 FTEs as shown in Table 15. Three students and two research assistants are also involved in MOLLER continuing the group's excellent track record in HQP training. Previous HQP were in particular trained on the QWeak experiment, that involved three Ph.D. students (who have all graduated) and two research associates.

The Canadian group is playing a very important role in the design of the experiment and it is planning to take significant responsibility during the construction stage. The group is currently responsible for two work packages: spectrometer development and integrating detector, which form the core contribution of the Canadian group to MOLLER. These contributions are critical to the success of the experiment and consequently the Canadian group has a high profile within the collaboration.

### 5.2.3 Required resources

Most of the funding for the construction of the experiment will be provided by the US DOE, with funding becoming available as early as 2017. The project breakdown and financial resource estimate for the Canadian contribution is shown in Table 16. The group is planning to apply to CFI for construction funds. Operation funds are expected to come from NSERC. Technical support for the project design and construction is expected to be provided by NSERC MRS (Alberta lead) and TRIUMF.

| **Institute** | **Name** | **FTE** |
|---|---|---|
| Grenfell | A. Aleksejevs | 0.2 |
| Acadia | S. Barkanova | 0.2 |
| Manitoba | J. Birchall | 0.2 |
| Manitoba | M. Gericke | 0.5 |
| Winnipeg | B. Jamieson | 0.1 |
| UNBC | E. Korkmaz | 0.1 |
| Manitoba | J. Mammei | 0.5 |
| Winnipeg | R. Mammei | 0.1 |
| Winnipeg | J. Martin | 0.1 |
| Manitoba | S. Page | 0.1 |
| Manitoba | W.T.H van Oers | 0.1 |

Table 15: Canadian investigators working on the MOLLER experiment, with corresponding research FTEs.

| **Stage** | **Time scale** | **Operation (k$/y)** | **Construction (k$)** |
|---|---|---|---|
| Design | 2016-2018 | 330 | 0 |
| Construction | 2018-2022 | 426 | 2,000 |
| Data taking | 2023+ | 330K | 0 |

Table 16: MOLLER project breakdown with resource estimate

## 5.3 Ultracold neutrons at TRIUMF

### 5.3.1 Research goals

The nEDM is an observable that (if non-zero) violates time-reversal (T) symmetry, and through the CPT (charge-parity-time) theorem, also violates CP-symmetry. The present upper limit on the nEDM is $2.9 \times 10^{-26}$ e-cm. The TRIUMF experiment aims to improve the precision on the nEDM by a factor of 30 with a next generation apparatus (referred to as Phase 2, below). An observation of a non-zero nEDM would be interpreted as a discovery of CP-violation, sources of which are permitted within and beyond the Standard Model (SM).

Ultracold neutrons (UCN) are neutrons of such remarkably low energies (less than 300 neV) that they can be stored in material, magnetic, and gravitational bottles. The nEDM experiment uses UCN by storing them in a room-temperature material bottle and measuring their Larmor precession frequency in combined electric and magnetic fields using Ramsey's method of separated oscillating fields. A dependence of the Larmor frequency on electric field indicates a non-zero nEDM. The nEDM experiment leverages a new source of UCN being constructed at TRIUMF, for first operation in late 2016. The source uses a unique technology, which is expected to surpass other ultracold neutron sources elsewhere; it is the only spallation-driven superfluid helium UCN source in the world.

In the long run, after completion of the nEDM experiment, an upgrade of the UCN facility to support 2 or more experiments is envisioned.

### 5.3.2 The Canadian team and its impact

The Canadian group consists of 17 faculty at six institutions, for a total equivalent of 6.2 FTEs as shown in Table 17. The group also includes 8 postdocs and research associates, 10 graduate students and 8 undergraduate students. Over the year 19 undergraduate students have been trained through the TRIUMF co-op student program for example. Hence the project is a unique training ground for HQP in particle physics within Canada.

The TRIUMF Ultracold neutron facility is expected to become the leading particle physics experimental facility located in Canada. Hence, SNOLAB (in astro-particle physics) and the TRIUMF UCN facility will be the core of the onshore particle physics program in Canada. The UCN source and UCN nEDM experiments are being constructed within a collaboration between Canada and Japan. The Canadian group is responsible for major components of the UCN source and nEDM apparatus.

Presently, the three leading UCN sources in the world are the turbine at the reactor of the Institut Laue-Langevin (ILL) Grenoble, the PSI spallation D2 source, and the spallation D2 source at Los Alamos National Laboratory (LANL). The TRIUMF UCN source is expected to achieve competitive UCN density by relying on superfluid Helium rather than solid $D_2$ for downscattering cold neutrons (i.e. cooling down neutrons). While operating at 0.8K is challenging, the superfluid helium option allows for long storage times (which compensates for the lower power of the TRIUMF beam) and allows for horizontal or near-horizontal extraction of the UCNs. Overall the TRIUMF technology is complementary to other solutions allowing for different experimental optimization. The TRIUMF nEDM experiment is pioneering the use of dual Xe/Hg comagnetometer that is expected to enhance the sensitivity of the experiments compare to competing experiments relying only on Hg comagnetometer. Hence the TRIUMF UCN nEDM experiment is expected to achieve world leading sensitivity.

| **Name** | **Institute** | **FTE** |
|---|---|---|
| C. Bidinosti | U. Winnipeg | 0.4 |
| J. Birchall | U. Manitoba | 0.3 |
| M. Gericke | U. Manitoba | 0.1 |
| B. Jamieson | U. Winnipeg | 0.5 |
| D. Jones | UBC | 0.3 |
| A. Konaka | TRIUMF | 0.2 |
| E. Korkmaz | UNBC | 0.3 |
| T. Lindner | TRIUMF/U. Winnipeg | 0.1 |
| K. Madison | UBC | 0.3 |
| J. Mammei | U. Manitoba | 0.1 |
| R. Mammei | U. Winnipeg | 0.9 |
| J. Martin | U. Winnipeg | 0.8 |
| T. Momose | UBC | 0.3 |
| S. Page | U. Manitoba | 0.1 |
| R. Picker | TRIUMF | 1.0 |
| J. Sonier | SFU | 0.1 |
| W. van Oers | U. Manitoba/TRIUMF | 0.3 |
| BAE Research Scientist TBD | TRIUMF | 1.0 |

Table 17: Canadian investigators working on the UCN project, with corresponding research FTEs.

### 5.3.3 Required resources

The resource requested and project stages are summarize in Table 18. The UCN source is currently being constructed with funding coming from CFI, TRIUMF and Japan (KEK). The UCN group intends to apply to CFI in order to upgrade the UCN nEDM experiment and reach optimum sensitivity. The total cost of the project is expected to be 12M$ with about 2M$ going to the source upgrade. Beyond the completion of the nEDM experiment, one or more experiments are expected to be constructed with support from CFI at a cost of about 5M$ per experiment.

Funds for HQP, travel and various research activities are provided by NSERC and through CRC (J. Martin tier 1) for a total of 385k$/year. A significant increase to 800k$ will be requested from NSERC in order to support the research effort using the UCN source.

Technical support is provided by TRIUMF for the construction and operation of the UCN facility. Technical manpower will also continue to be supported by CFI when IOF funds become available. Computing requirements are modest, ramping to 400 core-yrs/yr within the next 3 years, which can be obtained through Compute Canada and Westgrid.

| **Stage** | **Time scale** | **Operation (k\$/y)** | **Construction (k\$)** |
|---|---|---|---|
| UCN source construction | 2016-2017 | 385 | 11,200 |
| nEDM exp. operation and upgrade | 2017-2021 | 800 | 12,000 |
| Other UCN experiments | 2022+ | 800 | 10,000 |

Table 18: UCN/nEDM project breakdown with resource estimate

## 5.4 HALO

HALO is a dedicated supernova neutrino detector that began full operation at SNOLAB in May 2012. The dector 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 enhanvced 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.

### 5.4.1 Research goals

Recently over 1 kt of lead from the decommissioned OPERA experiment at LNGS in Italy became available, leading to the opportunity to increase the mass of HALO by more than a factor of ten. This larger detector would contribute significantly more to the physics opportunities that would arise from the next galactic supernova.

The use of the OPERA lead in a new supernova detector has been presented to the LNGS Scientific Advisory Committee in April, 2015, with a full proposal expected. A core group of HALO collaborators are forming the collaboration. The timescale for a formal letter of intent and a full proposal is 2016-17 with the strong possibility of detector R&D and construction in the 2017–22 window.

### 5.4.2 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.

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 a 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.

### 5.4.3 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 the University of Montréal, and Carleton, Queens, and Alberta MRS

| Member | Institution | FTE |
|---|---|---|
| F. Duncan | SNOLAB | 0.1 |
| J. Farine | Laurentian | 0.05 |
| C. Kraus | Laurentian | 0.15 |
| C. J. Virtue | Laurentian | 0.5 |
| S. Yen | TRIUMF | 0.5 |

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

| Member | Institution | FTE |
|---|---|---|
| P. Camus | Queen's | 0.1 |
| P. di Stefano | Queen's | 0.2 |
| G. Gerbier | Queen's | 0.6 |
| T. Noble | Queen's | 0.1 |

Table 20: Canadian investigators working on the NEWS project, with corresponding research FTEs.

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. During 2017-2021, computing resources will be employed in the design stage to optimize the new detector geometry and arrive at decisions on neutron detection technologies.

### 5.4.4 Outlook for the period 2021-2025

Following the R&D period envisaged in the 2017-2021 period, the upgraded HALO detector at LNGS may be constructed and running by 2021.

## 5.5 NEWS

NEWS (New Experiment With Spheres) utilizes 1.4 meter diameter ultrapure copper spheres filled with a light gas (*e.g.* Ne, He, or H) as a drift and amplification volume to detect the ionization induced by nuclear recoil arising from the scattering of a WIMP. Operating at pressures up to 10 bars results in an active target mass of several kilograms. Deployed at SNOLAB in a large water shield, the detectors can further control backgrounds by fiducializing the events.

### 5.5.1 Research goals

NEWS aims to achieve sensitivity to light WIMPs that are undetectable by other methods. In particular, it will be sensitive to masses as small as 0.1 GeV/$c^2$ with interaction cross-sections down to $\sim 10^{-38}$cm$^2$. Varying combinations of mass and cross-section sensitivity can be achieved with different gases. The technique can be applied to the study of coherent neutrino-nucleus interactions as well as the search for Kaluza-Klein axions, another potential candidate for Dark Matter. The current schedule calls for installing the detector in a one year period starting in 2017. Data-taking is expected to occur in the 2018-2020 period.

### 5.5.2 The Canadian team and its impact

The Canadian faculty and staff working on NEWS, listed in Table 20, are leading the effort, with international partners in France (CEA IRFU Saclay, Laboratoire Souterrain de Modane, Laboratoire du Physique

Subatomique et Cosmologie), Greece (Aristotle University) and Germany (TU München). Currently, two postdoctoral researchers and three PhD students in Canada are engaged in the project. As the host laboratory, SNOLAB is providing critical engineering support for the water shield and other site issues.

### 5.5.3 Required resources

NEWS is primarily supported by CFI and funds associated with a Canada Excellence Research Chair at Queen's. As mentioned previously, SNOLAB support in project management, designing a suitable water tank, other core infrastructure, and in filling and draining the tank as detectors are deployed and redeployed will be needed. TRIUMF support in shielding the sphere from cosmic rays during fabrication (if they are fabricated near TRIUMF) will be requested.

### 5.5.4 Outlook for the period 2021-2025

By 2021, the first run of NEWS should be over, with the option of continuing the experiment at SNOLAB or in another underground laboratory if the currently allocated space becomes unavailable. Application of the detectors to coherent neutrino scattering using a reactor source may also be considered. If the method proves successful, a larger detector to detect supernova neutrinos is also a possibility.

## 5.6 International Large Detector at ILC

The ILC is a proposed 31 kilometre electron-positron collider that will operate at a centre-of-mass energy between 200 and 500 GeV. The machine is also being designed to be upgradable to reach a collision center-of-mass energy of 1 TeV.

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. To meet the stringent spatial resolution requirements dictated by the ILC physics programme, the ILD proposes a TPC as the central tracking. The single hit transverse spatial resolution goal of 100 $\mu m$ 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.

### 5.6.1 Research goals

The primary goal of the ILC is to study new physics phenomena expected at the TeV level. Given the well-defined centre-of-mass energy and initial state quantum numbers, the ILC can make precision measurements to unravel LHC physics complexities at the TeV scale.

The LHC is now exploring the multi-TeV energy scale in proton-proton collisions. The LHC experiments have discovered a Higgs-like boson as predicted by the SM . It has been understood for a long time that there are intrinsic limitations to the ability of hadron colliders to study colour-singlet scalar particles, and that precision measurements, to the few percent level, are needed to place a new scalar particle correctly within our model of particle physics. The ILC is an ideal machine to address this question. The ILC is the perfect probe to study new physics, both through the production of new particle predicted by models of BSM physics and through the study of indirect effects of new physics on the W and Z bosons, the top quark, and other systems that can be studied with great precision. Both LHC and the ILC are needed to develop a comprehensive theory of fundamental particles and interactions.

A complementary approach is followed at the proposed circular collider projects such as the Future Circular Collider (FCC-ee, CERN) or the Circular electron-positron Collider (CepC, China). These two competing circular colliders concepts aim to collide electron and positrons beams in a 50-100km long tunnel at centre-of-mass energies of around 250 GeV with an instantaneous luminosity of about $6\times10^34cm^{-2}s^{-1}$(FCC-ee) at several interactions points. Construction of these colliders might start as early as 2021 for CepC and 2027 for FCC-ee. The 250 GeV option would serve as so-called Higgs factory with about $2 \times 10^6$ (FCC-ee) Higgs bosons from associated ZH production in five years at four detectors. A possible first stage of the collider could be operated for about two years at lower beam energies at the Z pole with an instantaneous luminosity of about $28 \times 10^34 cm^{-2} s^{-1}$ (FCC-ee) which would allow precision Z lineshape and asymmetry measurements with about three orders of magnitude more statistics than LEP. Currently, there is no Canadian activity on these projects but there is significant physics overlap with the ILC program.

### 5.6.2 The Canadian team and its impact

As shown in Table 21, a total of four Canadian faculty at three different universities are taking part in detector R&D work for ILD/ILC. One full-time research associate and one MSc student currently also contribute to the Canadian activities.

| **University** | **Name** | **FTE** |
|---|---|---|
| Carleton | Alain Bellerive | 0.2 |
| | Madhu Dixit | 1.0 |
| McGill | Francois Corriveau | 0.2 |
| Victoria | Dean Karlen | 0.1 |

Table 21: Canadian investigators working on ILD R&D, with corresponding research FTEs.

The Canadian team has trained in the past five years a steady number of graduate students (1 PhD, 6 MSc). It is also worth pointing out that several aspects of the R&D work carried out at Canadian institutes is appropriate for undergraduate projects. In the past five years, a noteworthy total of 16 undergraduate students participated in ILD related R&D work.

For the period 2017-2021, the overall involvement of Canadians on the ILD will depend on progress made towards the realization of the ILC. Section 8 comments on work at TRIUMF related to potential contributions to the ILC accelerator project.

Over the last two decades, Canada has been at the forefront of research for the development of novel detectors for the ILC. Researchers from Carleton, UVIC and TRIUMF have been involved in the development of Micro Pattern Gas Detector (MPGD) readout for the proposed Time Projection Chamber (TPC) of ILD; while researchers from McGill have been doing R&D with SiPM and Resistive Plate Chambers (RPC) for a forefront imaging digital calorimeter as members of the CALICE collaboration. Over the years, Canadian activities have shown steady progress in tackling important issues related to the development of these novel detectors. Canadian team members have made key contributions that are clearly recognized and aligned with the global international ILC effort, and the expertise resides in Canada for a strong participation in the ILC physics program.

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).

### 5.6.3 Required resources

A call for ILC experiment proposals could come as early as 2018 if there is a positive recommendation from Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT), and the approval by the Japanese Government in 2016. It is expected to take about nine years until ILC completion from 2018. Thus this may call for funding agencies around the globe to devote appropriate funding in 2017, to push ahead with the science proposed by the ILC TDR. Significant funding and/or technical resources requests in support of a strong Canadian participation in the ILC physics program is clearly directly dependent on the approval and construction timeline of the ILC.

# 6 Detector Development and Infrastructure

The development of novel techologies at the cutting edge of knowledge engages much of the time, effort and creative energy of experimental particle physicists. Consquently, 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. The latter two will be discussed in the following sections whereas 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 in the groups funded through the NSERC MRS program. Because these resources are so essential to the success of Canadian particle physics research, their support within NSERC is of the highest priority for the community. Consequently, maintaining the Major Resources Support 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. The MRS supporting the Groupe Technologique at the University of Montreal electronics expertise, which has played an essential role in many experiments across the country and in labs around the world over the years, is just one example of how critically the experimental physics community depends on the MRS program. For future experiments, it is important to ensure that Canada maintains its electronics capabilities and begins to develop expertise in the development of analogue ASICs.

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.

Most experiments with a Canadian involvement will draw on the expertise at TRIUMF and that lab has developed a "Gate-Review" process. This process provides an open and transparent 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. That openness and 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 is also pleased to see that SNOLAB has recently developed a "Gateway" process that is similar to the TRIUMF Gate-Review process and that the two labs are coordinating their efforts in supporting the community. 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.

The ability to access international facilities operating at the cutting-edge of this field is equally important. 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 CERN. 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 LHC and at J-PARC. In this Long Range Plan period it is important to recognize that such a model, and the funding implications, is likely to continue. 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 raises any consideration of such an Association to the level of Industry Canada or the Department of Foreign Affairs, Trade and Development.

# 7 Computing

Experimental subatomic physics projects often have significant compute and storage needs. In order to meet those needs, our community has been an early adopter of large-scale grid and cloud computing technologies and have been very active in establishing Canadian computational resources within universities, at TRIUMF and as part of Compute Canada. These resources support both the domestic program and act as an essential contribution to international projects.

## 7.1 Compute Canada

Funding for major Canadian Advanced Research Computing (ARC) resources is primarily provided through the Canada Foundation for Innovation (CFI), and those resources are managed, by and large, by Compute Canada. Compute Canada is a national not-for-profit corporation, whose members are the same research universities that host most Canadian SAP researchers. It acts as a national infrastructure provider, allowing large shared resources to be designed, procured and managed for the benefit of all Canadian university researchers, in all disciplines. Members of the SAP community have been among the leading advocates for national shared ARC infrastructure though leadership in either Compute Canada or its regional partners. SAP currently represents the largest disciplinary user of Compute Canada storage, with well over 4PB in use. Compute Canada also serves several thousand core-years per year (more than 3,000 to ATLAS alone) of computing capacity to the SAP community. As such, the relationship between the SAP community and Compute Canada is very important for both parties. The support of the SAP community is important to the continued funding success of Compute Canada and access to Compute Canada's world-class computing facilities and support is critical for many Canadian SAP projects. The importance of Compute Canada to SAP is growing as Canada sees a consolidation in CFI-funded computing centres and some computational tasks traditionally hosted at Canadian laboratories migrate to large shared ARC facilities.

The SAP community has large ARC needs, long planning horizons and is internally well-organized. As such, it is critical that the community plan for future ARC needs with the same diligence as for future accelerator and detetector facilities. In the current environment, this means that the community must organize responses to Compute Canada facilities planning exercises with clear statements of need and must work with the organization to ensure that those needs are met. Recently, Compute Canada has been awarded significant new capital funding and has ongoing operations funding from CFI. This is good news for ARC in Canada, and SAP is well positioned to benefit from the resulting infrastructure. The SAP community needs to ensure that this state persists.

## 7.2 HEPNET/Canada

HEPNET/Canada has been responsible for national and international network connectivity for the SAP 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 (FY2015-2017). The community provides input to HEPNET with an advisory committee, the members of which are appointed in consultation with the IPP director. The members are R. Tafirout (TRIUMF), C. Virtue (Laurentian), and A. Warburton (McGill).

HEPNET coordinates the network for the SAP 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. SAP is the largest user of the CANARIE network. CANARIE operates a national 100G backbone and provides a 2x100G transatlantic link.

A large fraction of our network traffic is generated by the ATLAS experiment. The TRIUMF ATLAS Tier 1 centre is connected directly to CERN with a 10 Gbps link (part of the LHCOPN network). In addition, TRIUMF and the four Tier 2 centres (SFU, Victoria, Toronto, McGill) are linked to the LHCONE network with 10-100G connections. The LHCONE network is a global routed network that connects all WLCG computing centres (including centres in the Belle-II project).

The computing situation in Canada is evolving and it will have a significant impact on the SAP network configuration. Compute Canada will commission its first set of new centres in 2016-2017, and further centres in 2017-2018. HEPNET will need to link the new centres to the LHCONE network and install new monitoring systems.

HEPNET has participated in high-speed demonstration projects with Caltech and other groups. In May 2014, HEPNET had dedicated access to the 100G transatlantic link and used it to test data transfers from Ottawa to CERN. In November 2014, HEPNET led a demonstration project where we transferred data from a single server in Victoria and to another server in New Orleans at 70 Gbps. HEPNET is one of leading members of the Canadian Software Defined Network (SDN) working group. SDN technology promises to revolutionize our use of the network by giving the computer application the ability to dynamically manage the network. HEPNET will continue to pursue R&D efforts focused on end-to-end solutions with high performance servers, storage systems and networks. This work has proven to be very valuable and has helped to establish strong links to industry.

### 7.2.1 The Canadain 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.

Six former staff are employed in industry and two are employed by CERN IT. Two graduate computer engineering students were co-supervised by the HEPNET director. Recently an ATLAS student did his authorship qualification work on cloud computing with this group.

HEPNET has employed approximately 50 undergraduate science, computer science or engineering 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.

### 7.2.2 Required resources

HEPNET uses a fraction of its MRS award to pay for a variety of small network equipment or port charges. HEPNET contributes to the lease of the network that connects SNOLAB to the local network provider. HEPNET also provides network monitoring systems to the computing centres and these systems will need to be refreshed in the new few years.

The director of HEPNET is actively involved in developing cloud computing systems for SAP applications (supported by non-NSERC funds). Industry is spearheading a global transition to cloud technology and the SAP research community is gradually migrating its facilities to clouds. The utilization of cloud technology is expected to accelerate in the 2017-2021 period and this work will benefit the SAP community. The cloud computing project uses Compute Canada and CERN facilities as well as other opportunistic resources in Canada, Europe and the United States. HEPNET has a small in-kind grant for cloud resources on Amazon EC2.

### 7.2.3 Outlook for the period 2021-2025

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 Tbps networks (1000G) to replace the 100G national backbones at the start of the next decade and computing centres will have multi-100G or 1000G links to the national backbones by 2020 and 2025, respectively.

HEPNET will continue to play an important role for the SAP 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 Tbps 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. HEPNET plans to continue its strong collaboration with its 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 should continue to make HEPNET an excellent project to attract and train exceptionally talented staff and students.

# 8 Particle Accelerators

Particle accelerators play an important role in studies of fundamental physics and 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, by the ATLAS and CMS collaborations, and for many other studies, including searches for BSM physics. They play a critical role also in neutrino experiments such as T2K, where very intense proton beams are needed to create the neutrino beams required by the experiment. Closer to home, they 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 new 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.

## 8.1 Research goals

For high-energy particle physics applications, an important goal for the future is the development of high-gradient acceleration technologies, using either conventional superconducting cavities, or other techniques such as Plasma Wakefield acceleration. Work is also needed in advance of a planned luminosity upgrade to the HL-LHC starting around 2024. The so-called High-Luminosity LHC (HL-LHC) will operate at instantaneous luminosities up to 7.5 times the LHC design luminositiy of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. There are also longer-term goals related to the next generation of energy-frontier machine, likely either a linear electron-positron collider, or a large “future circular collider” (FCC) that would have a circumference of around 100 km. A conceptual design report for such a machine is planned for sometime in 2018, in time for the next update of the European Strategy for Particle Physics.

## 8.2 The Canadian team and its impact

The Canadian community of accelerator physicists is centred at TRIUMF, but has members at universities across the countries, with diverse interests in particular aspects of the field.

Canada contributed the construction of the Large Hadron Collider at CERN, via the contributions to the LHC injection kickers and the construction, in collaboration with industrial partners, of 52 twin-aperture quadrupole magnets for the beam cleaning insertions of the LHC. The Canadian contributions to the LHC represented a $40M investment, with 90% of the funds spent in Canada. CERN is currently already preparing for a future luminosity upgrade of the LHC, beginning around 2024. Through TRIUMF, Canada has been invited to contribute to this work, via the supply of warm quadrupole magnets for the interaction regions, beam-beam accelerator physics calculations, and beam halo instrumentation.

The Canadian community is involved also in R&D projects aimed at future facilites, via development and testing of Superconducting Radio-Frequency (SRF) accelerating cavities for the ILC, as well as efforts to develop new higher-gradient accelerating technoloiges, such as Plasma Wakefield acceleration, which TRIUMF scientists are pursuing both within the AWAKE Collboration, based at CERN, and locally, with plans to develop an Ultra-high gradient facility at TRIUMF.

TRIUMF is also involved in the important activity of training the next generation of accelerator physicists. In the last several years TRIUMF has organized a Accelerator Physics course offered through UBC and the University of Victoria. Ten graduate students are presently registered in Accelerator Physics projects at TRIUMF and this number is growing as more students and associated universities see the benefit of the expertise and infrastructure at TRIUMF, for the training of HQP. The group proposes to grow this program with the addition of key hardware to form an accelerator study centre, with infrastructure including a small student designed cyclotron, a small electron ring, a diagnostic test facility and an ion source test stand with an analyzing station.

A list of present activities of the accelerator community is provided in Appendix A.

# 9 IPP Support for the Community

The goal of the IPP is to coordinate and support particle physics research in Canada. IPP coordinates and nurtures coherent efforts on large international projects, thereby optimising Canada's impact.

The main resource of the IPP is the group of eight Research Scientists. The IPP Research Scientists are world-class physicists with international reputations and are, in every way, peers of university particle physics faculty except that they are not required to teach classes. This allows them to take on additional research-related leadership responsibilities in support of the IPP community, especially those that require an extended time commitment at the international laboratories where many of our experiments are carried out. For example, they play leadership roles in the operation of the experiments, senior management of the collaborations and in the analysis of data at the laboratory. Their full-time research activity allows them to assume positions of responsibility within the IPP program in collaboration with their university faculty colleagues. They are in a position to take on technical and group coordination responsibilities at various stages of an experiment. Many have spent and are spending extensive periods of time located on-site at the experiments acting as IPP group or experiment-wide coordinators during critical periods in the design, construction, commissioning, and operation. IPP Research Scientists hold faculty or adjunct faculty positions at their host university. Presently two Research Scientists are located at each of McGill, Toronto, and Victoria, and one each at the University of British Columbia and Queens University. In order to host a Research Scientist, a university must be an Institutional member of the IPP and have an existing group working on an IPP Project. Although hosted at a particular university, each IPP Research Scientist is an invaluable resource of the broader experimental particle physics community since all researchers on the projects where a Research Scientist focuses effort benefit from them. They are a key element in keeping the Canadian community at the forefront of international projects and enable our community to "punch above our weight" in this field. It is essential for the success of particle physics in Canada that this program be fully supported going forward.

In addition, the IPP operates the IPP CERN Summer Student program which trains undergraduate students, an extremely successful program that should be supported going forward. CERN operates one of the world's premier particle physics undergraduate summer student programs and provides an outstanding international research and teaching environment bringing together students from around the world. Over an eight-week period in July and August it provides a series of introductory lectures on accelerator science and particle physics experimentation. During their time at CERN, students attend lectures each morning and work on some aspect of the CERN research program during the remainder of the day. Many of the students go on to careers in particle physics research or become leaders in other scientific disciplines. IPP provides the opportunity for Canadian undergraduate students to participate in this program. Each year since 2008 the IPP has sponsored via a competitive national fellowship between 3 and 6 Canadian students to participate in a summer student program that incorporates them into the CERN summer student program. The students, after being selected in an annual national competition occurring in January, are given a list of IPP members seeking to sponsor and supervise a student in May and June. The students move to CERN for July and August to participate in the CERN Summer School program. Supervisors can have them move to CERN earlier if the May/June project is best done at CERN. IPP supports their airfare and cost in July and August at CERN. This provides an excellent opportunity for IPP to reach out to parts of the country that have not traditionally had a strong involvement in particle physics: of the thirty-seven students who have been given this opportunity since 2008 twelve were enrolled in universities that are not IPP Member Institutions. On graduation, 75% of the students from this program go on to graduate school with the majority of those pursuing a PhD in particle physics.

IPP has consulted with its members on how it might move to support the theory community where there is an important need not already being met and in a manner that can have the greatest impact on meeting that need. It has been recognized that many theory graduate students and postdocs (HQP) do not normally have the same degree of international experience as most experimental particle physics HQP, a benefit that enhances their career progress, whether they remain in the field or move into Canadian industry. As a consequence, IPP has requested funds to launch a pilot program, the “Early Career Development Fellowship”, that encourages and broadens the international experience of outstanding theory HQP (senior PhD students and postdocs) with a fellowship enabling them to be present for a period of between two weeks and six months at an international advanced school, laboratory, or institute. The Fellowships will be awarded via a competitive process, limited to students and postdocs supervised by NSERC-funded faculty, and at most two would be awarded per institution per year. Funds awarded are intended to cover travel and living expenses. The Early Career Development Fellowship would enable NSERC to support the very best early-career scholars across the country in a manner that benefits theory groups of all sizes. The students and postdocs will submit applications with their supervisors that demonstrate the excellence of the candidate and the value the individual will gain from the Fellowship. The expectation is that early-career scholars, particularly from smaller centres, will experience a significantly broader experience in research and a more mature view of the profession. The program will be run on a trial basis for five years. If funded, and the pilot-program indicates that this is effectively fulfilling a real need of the community, IPP would want to continue it in the future.

# 10 Program Priorities

Going into the 2017-2021 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 are presented in Figure 1. This shows the evolution of each project from the start of funded contruction following approval (orange) through to the end of physics data-taking (blue).

## 10.1 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 supported from the NSERC subatomic physics envelope. Canadian particle physics faculty, both theorists and experimentalists, 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. 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 continue to receive the fraction of the envelope (approximately 15%) that has historically been allocated to theory Discovery Grants in both nuclear and particle physics.

## 10.2 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 making important, and in some cases critical, impact on the experiment. It can be expected that 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.

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 ($> 70\%$) 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 only way of making a major discovery.

### 10.2.1 Energy Frontier

At the energy frontier, there is ATLAS. 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 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 can be expected to contribute of order $10M in equipment costs to the detector upgrades, in addition to the associated infrastructure and labour costs. In addition, there is an expectation that Canada, through TRIUMF, will contribute to the upgrade of the machine. This will begin in the period of this Long Range Plan and it is important to define those contributions early.

### 10.2.2 Precision Frontier

Belle II and UCN/nEDM are the two essential projects at the precision frontier that probe well above the TeV scale in a manner fully 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 UCN/nEDM 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 in 2016 and by the end of 2017 at the latest. A negative Japanese decision would likely see the interested proponents turn their attention to other high energy electron-positron collider projects that are on the horizon.

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 or design stages and are awaiting funding decisions with plans to take data beyond 2021 should be supported at an appropriate level as their physics goal is to address a “Big Question” in an effective manner. NA62 is one such experiment that is taking data in 2017-2021 whereas MOLLER and g-2 are in the design and R&D phases, respectively. It is not expected that NA62 will grow substantially in numbers of Canadian researchers. If MOLLER moves successfully through the U.S. DOE CD-process and is approved, it can be expected that the Canadian team members will increase the fraction of research time they allocate to the project and additional people may join that effort. For g-2, it is still at the R&D and conceptual phase, but the pay-off here could be substantial if the measured ($> 3\sigma$) Brookhaven muon g-2 anomaly is real.

### 10.2.3 Neutrino Oscillations

T2K is the IPP flagship experiment measuring the neutrino mixing angles of the MNS matrix taking data during the 2017-2021 period. Depending on its value, a non-zero CP-violating phase, $\delta_{CP}$, may be measured by T2K and its competitor NO$\nu$A before 2021. This would be a major discovery. There are a significant number of Canadian researchers allocating a large fraction of their research time to T2K and a large investment has been made in this experiment. This is one of the essential projects of IPP.

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.

### 10.2.4 Direct Dark Matter Detection

DEAP-3600 and SuperCDMS are two essential projects at SNOLAB searching for dark matter and which will be collecting data in the 2017-2021 period. There has been significant capital investment in DEAP and it is crucial that the experiment be supported to ensure that the science from this investment is produced. It will also determine if the single phase liquid argon technology can achieve the ultimate sensitivity in a subsequent upgrade to DEAP-50T. SuperCDMS has a smaller team that is part of a large primarily U.S. funded experiment. It will take data with a 30 detector system having a total mass of 30 kg during this Long Range Plan period. Preparations for upgrading the experiment to 200 kg, which extends the reach to the neutrino floor, will begin around 2019. The SuperCDMS is sited in one of the SNOLAB Ladder Labs and would stay in that space for the upgrade.

PICO and NEWS are important experiments taking data during this period where there is very active Canadian involvement with a reasonable, though modest, number of Canadian grant-eligible researchers allocating significant time to their respective projects. There is strong physics case for both experiments each with the potential to make a dark matter direct-detection discovery focused in the low mass region.

### 10.2.5 Neutrinoless Double-beta Decay

There are two neutrinoless double-beta decay experiments taking data during the Long Range Plan period, SNO+ and EXO. Both have a significant number of researchers allocating a large fraction of their research time and have a fairly substantial total number of people vested in each experiment. 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. EXO-200 will run at WIPP and is designed to measure neutrinoless double-beta decay using an entirely different method with different nuclei. Given the investment in developing the experiments and the commitments of grant-eligible researchers to these experiments, coupled with the importance of this potenial discovery, both are essential projects at this stage. R&D work on EXO intended to enable it to be upgraded to 5 tonnes, as nEXO, is underway. Should that program succeed technically as well as in getting approval from the U.S. DOE, the intention is to move it to SNOLAB. Such a move would require the commitment of appropriate space from SNOLAB. It could be competing with other projects for space in the SNOLAB Cryopit. nEXO has the potential to become an essential IPP project.

### 10.2.6 Other Projects

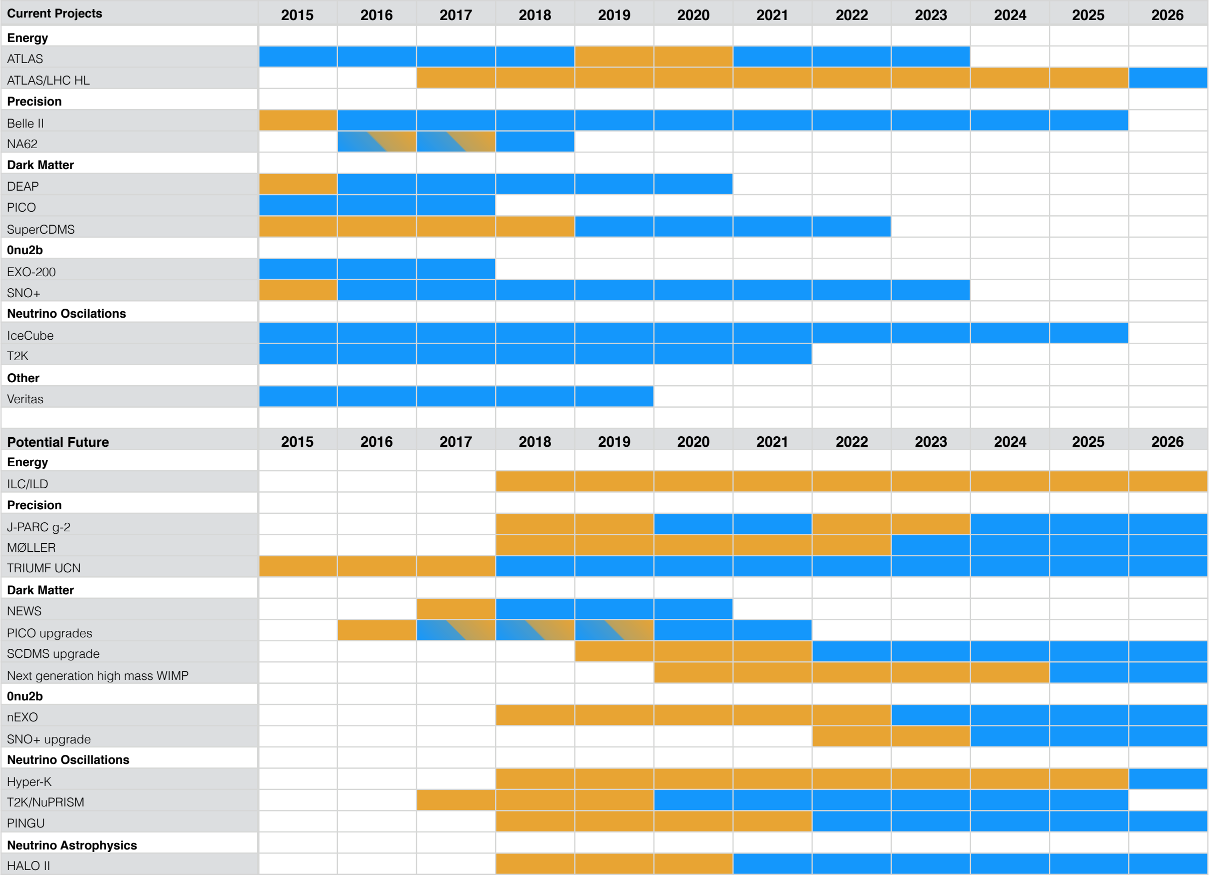
The program should also support small, low cost projects with a compelling physics case but which involves a small group of people taking advantage of particular technological opportunities that enable the project and keep the costs low. HALO is an example of such an experiment. Upgrading to a larger detector at LNGS would require additional resources. Before allocating significant Canadian resources to the project, a larger number of Canadian participants with substantial fractions of their research time should be dedicated to it. VERITAS is another example of such a project. It will begin its ramp-down phase during 2017-2021.

For a balanced program it is important to ensure that some resources are allocated to new ideas and projects that are in the early stages of development.

## 10.3 Additional Considerations for Major Potential Future Projects

Concerning the future neutrino experiments focused on measuring the mixing angles and determining the mass heirarchy, three projects on which a number of Canadian researchers are working but which are not yet funded are Hyper-Kamiokande (HK), T2K/NuPRISM and PINGU (in IceCube). Decisions on funding for these projects are expected in the early part of the period of this Long Range Plan. The groups are already collaborating in a combined NSERC RTI request for R&D on photodetector technologies that can be used in any of these experiments. NuPRISM is under consideration by the J-PARC Program Advisory Committee. Stage 1 approval could lead to the project moving forward rapidly in association with a potential extension of the T2K program into the mid-2020s followed by Hyper-Kamiokande. If that occurs, a request

Figure 1: Timelines of experimental projects. Blue corresponds to physics data-taking, while orange corresponds to funded construction following formal approval of a project.



| Current Projects | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Energy** | | | | | | | | | | | | |
| ATLAS | 🟦 | 🟦 | 🟦 | 🟦 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | | | |
| ATLAS/LHC HL | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟦 |
| **Precision** | | | | | | | | | | | | |
| Belle II | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | |
| NA62 | | 🟦🟧 | 🟦🟧 | 🟦 | | | | | | | | |
| **Dark Matter** | | | | | | | | | | | | |
| DEAP | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | | | |
| PICO | 🟦 | 🟦 | 🟦 | | | | | | | | | |
| SuperCDMS | 🟧 | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | | | | |
| **0nu2b** | | | | | | | | | | | | |
| EXO-200 | 🟦 | 🟦 | 🟦 | | | | | | | | | |
| SNO+ | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | |
| **Neutrino Oscillations** | | | | | | | | | | | | |
| IceCube | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | |
| T2K | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | | |
| **Other** | | | | | | | | | | | | |
| Veritas | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | | | | |

| Potential Future | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Energy** | | | | | | | | | | | | |
| ILC/ILD | | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 |
| **Precision** | | | | | | | | | | | | |
| J-PARC g-2 | | | | 🟧 | 🟧 | 🟦 | 🟦 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 |
| MØLLER | | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 |
| TRIUMF UCN | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 |
| **Dark Matter** | | | | | | | | | | | | |
| NEWS | | | 🟧 | 🟦 | 🟦 | 🟦 | | | | | | |
| PICO upgrades | | 🟧 | 🟦🟧 | 🟦🟧 | 🟦🟧 | 🟦 | 🟦 | | | | | |
| SCDMS upgrade | | | | | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 |
| Next generation high mass WIMP | | | | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 |
| **0nu2b** | | | | | | | | | | | | |
| nEXO | | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 |
| SNO+ upgrade | | | | | | | | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 |
| **Neutrino Oscillations** | | | | | | | | | | | | |
| Hyper-K | | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟦 |
| T2K/NuPRISM | | | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | |
| PINGU | | | | 🟧 | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 |
| **Neutrino Astrophysics** | | | | | | | | | | | | |
| HALO II | | | | 🟧 | 🟧 | 🟧 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 |

of approximately \$5 million to produce photosensors and readout electronics can be expected in the CFI competition following the project approval, expected in 2017. PINGU is also awaiting a funding decision and if approved the Canadian proponents can be expected to request on the order of \$10M-\$15M from CFI in the upcoming competition. HK has a broad and compelling physics case and it can be expected that many in the T2K experiment will transition to HK should a positive Japanese decision for funding it be made in a timely manner. Given the level of investments, it can be expected that such a decision may be related to a Japanese decision to fund the ILC as it is unlikely that both ILC and HK will be funded by Japan. If HK is funded, the broad scientific program and compelling physics case for this experiment can be expected to draw a reasonably large number of Canadian researchers and would likely see this becoming a essential project for IPP. It would involve a request of order \$10M-\$15M from CFI in the anticipated 2018-19 CFI competition. Depending on the outcome of the host-country funding decisions, there are scenarios that may have movement of researchers between these projects or possibly other new projects.

Looking beyond 2017-2021 in the direct dark matter detection sector, the next generation experiment will require substantial investments, on the order of \$50M, and suitable space in SNOLAB may be a limiting factor. For that level of funding it is important to have significant consolidation in Canada with almost all researchers focused on direct dark matter searches working on the same experiment. Otherwise, the community runs the likely risk of having significantly reduced roles and impact on foreign driven experiments. Early in the period of this Long Range Plan, that community will have to begin a consolidation plan.

## 10.4 Summary of Particle Physics Priorities Looking Forward

- As the SAP envelope increases, it is essential for the subatomic physics theory community to be secured in receiving the approximately 15% of the SAP envelope.
- 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. IPP strongly endorses contributions from Canada, through TRIUMF, to the upgrades of the LHC accelerator complex.
- Belle II and UCN/nEDM are essential projects at the precision frontier and will take data throughout and beyond this Long Range Plan period and beyond. It is important to maintain a balanced program and support of smaller, more focused precision frontier efforts including NA62 and if funding decisions in the U.S. and Japan are favourable, MOLLER, and g-2 at J-PARC. For these latter experiments to see Canadian funding grow, they should have more investigators investing more than 70% of their research FTEs into the projects.
- The community is waiting for a Japanese decision on the ILC. Should Japan proceed with the ILC, IPP sees this becoming a high priority initiative of our community.
- IPP also deems it to be essential to our program to have one world-leading project in each of these areas:
  - an experiment probing CP violation and/or mass heirarchy in neutrino oscillations;
  - a neutrinoless double-beta decay experiment;
  - a direct DM search experiment.

  Each of these efforts will require considerable resources overall and therefore it is essential that substantial contributions come from foreign partners, including for those projects sited in Canada. Which experiment in each area goes forward will, as with the energy and precision frontier experiments, depend on:

  - whether its scientific relevance, reach and competitiveness places it at the forefront of the field so that at the time a Canadian funding decision is made there must be the expectation that the experiment will still be at the cutting edge by the time it's taking data and publishing physics results;

  - successful solutions to its major/key technical challenges having been proven;
  - it having a significant contingent of Canadian proponents from multiple institutions committing most of their research time, with the Canadian leaders and a reasonable fraction of the contingent committing at least 70% of their research time to the project, consistent with the overall complexity and associated costs of the project;
  - major foreign resource commitments having been secured or likely to be secured, with the final Canadian funding decision contingent on successfully securing those foreign resources; and
  - for a project sited at SNOLAB, sufficient lab resources, including appropriate space, ready to be committed by SNOLAB to the project.

- 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.

- It is essential to ensure some funds, on the order of 5% in total, from the SAP envelope are available for detector and accelerator R&D because the future of the field depends on it and it provides outstanding HQP training opportunities in skills that are directly transferable to industry. The message here is simple: “Don’t eat your seed corn.”

- 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 during this period.

- 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.

- IPP strongly endorses with highest 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.

- The CFI MSI program that supports SNOLAB and Compute Canada are absolutely essential for our field to function now. IPP strongly endorses any and all efforts on the part of NSERC to provide messages of support for this 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.

# 11 Budget Scenarios: Opportunities and Challenges

In all three Nobel Prizes in Physics awarded in particle physics over the past 10 years - the discovery of neutrino oscillations (2015), Higgs mechanism (2013), and CKM CP violation (2008) - Canadian experimentalists have been key players. Arthur McDonald received the 2015 Nobel Prize and the ATLAS and BaBar experiments were cited in the Nobel announcements for providing the critical verification of the work of the theorists who received the 2013 and 2008 Nobel prizes, respectively. The IPP community has a set of aspirations aligned with its existing strengths and a suite of complementary experiments: at the energy and precision frontiers; the study of mass heirarchy and CP violation in neutrino oscillations; neutrinoless double-beta decay; and experiments that directly search for dark matter particles. These cover the areas where the next major discovery will be made while not over-covering them as they are entirely complementary. With increased funding to the SAPES envelope the IPP community will be able to cover all the discovery bases and ensure that Canadians are again key players for Nobel Prizes in particle physics for the foreseeable future. Without increases, difficult decisions will have to be made; some projects will not go forward, leaving a very real possibility of missing a major discovery.

Even without covering those bases, 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. CFI IOF funds have covered much of that support in the past, but IOF funds only last 5 years whereas the experiments, as can be seen by the timelines, run considerably longer than that and require that technical support over their full duration. Moreover, technical support that TRIUMF had been able to provide to the community is now being stretched with the demands that have arisen from the ARIEL construction program and TRIUMF has in the past five years introduced full cost recovery for technical support. The only solution our community has found in dealing with these developments is for increasing amounts of technical support to be funded from the project grants in the NSERC subatomic physics envelope. These developments also make the MRS program even more important. Participation in international projects also requires significant contributions to "Common Funds" which pay for common maintenance and operating funds that have also been significantly increasing.

All of this results in less funding within a project going towards HQP. Going forward this risks also seeing the IPP community losing out on high discovery-potential projects. With an increase in funding that merely makes up for the increases in the technical, maintenance and non-HQP operations costs, the IPP community will be able to continue to train the same number of HQP as they do now. But there will be insufficient funds to cover the full range of discovery potential projects. An increase that significantly exceeds this minimal level will mean that the entire IPP community, experimentalists, accelerator physicists and theorists, will be able to train more HQP and, depending on the levels of the increase, approach the full capacity of the community to train highly qualified personnel for the benefit of Canadian society.

# 12 Summary

Canadians have played a key role in the science leading to all three particle physics Nobel Prizes awarded in the past decade. In order to ensure Canada will continue to be a key player in the Nobel Prizes in particle physics in the future, the envelope will have to ensure that all of the discovery bases 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 key, if not 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 TRIUMF Accelerator Science Appendix

(14 August 2015 Submission by TRIUMF Accelerator Group for the Subatomic Physics Long Range Plan 2017-2021)

## A.1 Target Ion Source Development ISAC

### A.1.1 New target technology

Proton induced ion production from a variety of target materials such as SiC, Ta, ZrC, Nb, UCx have been developed at ISAC and are in more or less routine use. New target concepts have been proposed which could lead to new beams or enhance the yield from existing beams. New target materials like carbon nano-tubes are being considered that would enhance the diffusion and effusion of the active species with enhanced target lifetimes. Other investigations include two step targets where a neutron generator material like tungsten is bombarded by the protons and creates neutrons that fission an actinide target material. The two step mechanism would provide neutron rich isotopes in ISAC with less isobaric contamination than from direct spallation.

### A.1.2 Target development

Each new beam from ISAC requires some beam development that presently is being done on-line. On-line testing reduces experimental time from the science program. In order to systematically develop new target materials we propose to establish a new materials laboratory with equipment to study material properties pertinent to the production of RIBs. The goal is to gain better understanding of the complex processes occurring inside the target to maximize the yield. The TRIUMF cyclotron provides the world's highest power ISOL driver at 50kW. A particular focus of the target development would be to better understand the operation of the targets for the highest beam powers where ISAC could push beyond other facilities in terms of intensity and species.

### A.1.3 On-line source development

ISOL beam production efficiency is dependent not only on production and release from the target but also on the efficiency of ionization in the associated ion source. The target/ion source combination has to be optimized for each species. Certain gaseous species which are not surface ionisable will only find efficient ionization from an ECR source. We propose to develop an ECR source that can withstand the harsh conditions of the target environment. In addition many new species have been selectively ionized using resonant excitation of outer shell electrons using lasers (Laser Ion Source - LIS). An IGLIS source is being developed that provides further selectivity by suppressing surface ionization and providing mass selective transport of the laser ionized species.

### A.1.4 ISAC target modules

The ISAC radioactive ion beam facility came online in 1996. To date four target modules have been in active service. The target modules have to exist in a harsh environment and as such are starting to show signs of deterioration leading to reduced performance and reliability. We propose to design, build and test a new module based on the ISAC experience as well as incorporating new ideas from the ARIEL development.

## A.2 ARIEL2.5 (ARIEL Developments outside CFI)

### A.2.1 Conditioning stations

A conditioning station allows a target assembly to be tested and High Voltage conditioned in near-final conditions prior to installation on-line. A conditioning station has been operational in ISAC for the last few years and has proven effective at pre-screening and preparing targets before final installation. The goal of this project is to design and produce two conditioning stations for ARIEL, one for electron targets and one for proton targets.

### A.2.2 Laser ion source east station (ALIS-E)

Laser ion source capability will initially be installed in the west station only. The ARIEL laser ion source east(ALIS-E) is needed to ionize the rare isotopes produced in the ARIEL east station. The element selective ALIS will be the work-horse ion source for delivering intense, clean RIBs from the isotope production target. This is done through element selective, precisely tuned laser excitation and ionization. ALIS requires a temperature stabilized cleanroom enclosure located in the ARIEL RIB annex to provide a stable operating environment for 24/7 RIB delivery.

### A.2.3 Hot cells - ARIEL

Extraction and disposal of an irradiated target from the Target Module, and installation of a fresh target, must be done in a Hot Cell to protect the worker from radiation exposure. A Hot Cell is a ventilated enclosure with shielded walls, a special shielded viewport, and tele-manipulators used for materials handling. The ARIEL building layout allows installation of a modular Hot Cell system, with interlocking lead and steel panels that will form the outer walls, roof and floor of the enclosure. The dimensional constraints of the building dictate the use of metal shield panels rather than cast-in-place concrete forms.

### A.2.4 MRS for LEBT

The ARIEL low energy beam transport will be initially equipped with pre-separators with a resolution of 300 and a high resolution spectrometer (HRS) with a resolution up to 20000. Delivery of two simultaneous beams will be limited to one very light beam (8Li) that can be selected by the pre-separator and one high mass beam that can be separated in HRS. To allow the delivery of two higher mass beams we plan to add a Medium Resolution Spectrometer (MRS) with a resolution of 5000. The MRS will enable reduced beam tuning times for beams that don't require the highest resolving power compared to the HRS.

### A.2.5 Conventional chemistry lab

In order to handle various target materials for the ARIEL targets and chemically clean parts a conventional chemistry lab is required.

### A.2.6 High power converter

Phase I of the TRIUMF e-Linac is now installed with 30MeV capability. Plans are underway to install photo-fission production targets up to 100kW for the ARIEL2 project. The concept involves a two stage process. Electrons bombard a thin converter positioned in front of the target container to create bremsstrahlung photons. The photon cone in turn bombards the downstream actinide target material to produce fissions. TRIUMF has plans to upgrade the present e-Linac to its full 50MeV and 10mA design capability in the next several years. The 500kW beam power is beyond present engineering capabilities with the biggest challenge being in the converter design. We propose to initiate a high power converter project that would set as a goal to push current converter technology beyond 100kW and eventually to the full ARIEL design goal.

## A.3 Isotope mining from proton station

To date the ISAC spent targets are treated as radioactive waste and prepared for disposal. In reality the targets contain many longer lived species that would be of scientific interest particularly to explore new tools for nuclear medicine diagnosis and therapy. For example with beams from the new proton beamline (BL4N) and associated target station, ample amounts of Rn-211 can be produced, collected, and extracted for shipment to the appropriate collaborators. The At-211 is generated in transit through the decay of Rn-211. TRIUMF will focus on demonstrating the production, packaging, and shipment of Rn-211 generators (from thorium targets). Radiopharmaceutical production of novel theranostics will be explored. The multiuser capability of ARIEL will enable sufficient amount of beam time for this program. Mining the species of interest from the target material will require hot cells, hot chemistry and significant remote handling capability. In addition to mining the target material the ISOL process can be used to produce and separate small quantities of rare isotopes from target material for development studies. In this case targets at the end of the run can be heated, products ionized, separated on-line and deposited in a collection station.

## A.4 Second simultaneous accelerated beam

Even though ARIEL will provide the capability to deliver three simultaneous radioactive beams only one of the beams will be an accelerated beam since there is only one RFQ/DTL to reach medium energies. In order to decouple the medium energy and high energy areas a second RFQ/DTL combination can be added to allow simultaneous acceleration of a second RIB. In this way accelerated beam experiments can be scheduled simultaneously in ISAC-I and ISAC-II.

## A.5 ARIEL3 Future developments

### A.5.1 TARIF fragmentation of RIBs

TARIF or TRIUMF Accelerated RIBs for Ion Fragmentation is a new large scale proposal where neutron rich RIBs of high intensity from ISAC or ARIEL are accelerated in ISAC-II and injected in a new booster linac or synchrotron and accelerated to fragmentation energies. The goal is to reach RIB isotopes further out on the neutron rich side than can be reached with ISOL or standard fragmentation.

### A.5.2 TCR cooler ring

A cooler ring can be added either to take the ISAC-II beam directly or after fragmentation. The ring would provide a capability for experiments with stored secondary beams that is unique in the world. The envisaged physics programme is rich and varied, spanning from investigations of nuclear ground-state properties and reaction studies of astrophysical relevance, to investigations with highly-charged ions and pure isomeric beams. The TRIUMF Cooler Ring TCR might also be employed for removal of isobaric contaminants from stored ion beams and for systematic studies within the neutrino beam programme. In addition to experiments performed using beams recirculating within the ring, cooled beams can also be extracted and exploited by external spectrometers for high-precision measurements.

## A.6 Cyclotron development

### A.6.1 High intensity upgrade

To support the new ARIEL proton line (BL4N) the cyclotron beam intensity must be ramped from the present 300A to 400A. Developments and infrastructure are required to achieve this goal. An upgrade to the H- source is required to improve the beam brightness. Beam studies and new centre region hardware are required to deal with the enhanced space charge. Presently TRIUMF cyclotron tuning studies are limited by the lack of a high power tuning dump. Beams must be developed at low duty cycle or sent down BL1A. Low duty cycle operation is useful to determine first order optics but not to diagnose high power heating problems or halo formation. High intensity beam operation down an operating beamline is restrictive due to optics/hardware constraints and scheduling conflicts. We propose to design and build a high power beam dump in close proximity to the cyclotron that would serve both for high intensity development and isotope production.

## A.7 External projects

### A.7.1 Electron Ion Collider

The US long range plan calls for the construction of an Electron-Ion Collider (EIC). In kind contributions from TRIUMF accelerator physicists and engineers could be foreseen to support this construction with the goal to give Canadian scientists a place at the table while engaging in a cutting edge accelerator project.

### A.7.2 Hi-Lumi LHC

The Large Hadron Collider (LHC) is the world's most powerful particle accelerator, the largest scientific instrument ever built to explore the physics high-energy frontier. To extend its discovery potential, the LHC will need a major upgrade around 2020 to increase its luminosity (rate of collisions) by a factor of 10. With the upgrade, the LHC will push the limits of human knowledge beyond the Standard Model of particle physics. TRIUMF contributed to the LHC construction in several areas, and a subset is selected for the luminosity upgrade: supply of warm quadrupole magnets for the interaction regions, beam-beam accelerator physics calculations, and beam halo instrumentation. These activities contribute to TRIUMFs role as Canadas steward for the advancement of particle accelerators and detection technologies directly from the delivered equipment and by the recruiting and training of early career personnel. The production of quadrupole magnet coils with a new level of ionizing radiation resistance and the development of halo monitors with un-paralleled sensitivity are both opportunities for innovation (particularly the latter). Hi-Lumi is an exciting and challenging project and Canada through TRIUMF should continue to support CERN and cutting edge science.

### A.7.3 International linear collider

The International Linear Collider will allow physicists to explore energy regimes beyond the reach of today's accelerators. A proposed electron-positron collider, the ILC will complement the Large Hadron Collider. With LHC discoveries pointing the way, the ILC a true precision machine will provide the missing pieces of the puzzle. The 31km linac is a superconducting radio-frequency (SRF) project of unprecedented size that pushes present technology to the limits. Completing the project will demand a global solution. TRIUMF's SRF team and industrial partner PAVAC are ready and able to support this huge initiative. Discussions between TRIUMF-SRF and PAVAC are on-going at how to advance PAVAC from a SRF cavity producer to a full cryomodule producer.

### A.7.4 Future circular collider

Future Circular Collider (FCC) is an integral conceptual design study for post-LHC particle accelerator options in a global context. The collaboration is open to scientific institutes and companies of any size from all nations. The Future Circular Collider study has an emphasis on proton-proton and electron-positron (lepton) high-energy frontier machines. It is exploring the potential of hadron and lepton circular colliders, performing an in-depth analysis of infrastructure and operation concepts and considering the technology research and development programs that would be required to build a future circular collider. A conceptual design report will be delivered before the end of 2018, in time for the next update of the European Strategy for Particle Physics. TRIUMF accelerator physicists already with ties to CERN through present beam dynamics collaborative investigations are in a position to make an impact in the FCC conceptual design report.

### A.7.5 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 Wakefield acceleration is a rapidly developing field which appears to be a promising candidate technology for future high-energy accelerators. The AWAKE project has been proposed as an approach to accelerate an electron beam to the TeV energy regime in a single plasma section. To verify this novel technique, a proof-of-principle demonstration experiment is proposed using 400 GeV proton beams from the Super Proton Synchrotron at CERN to drive plasma wakefield acceleration and accelerate a GeV scale electron beam. AWAKE would be the worlds first proton-driven plasma wakefield acceleration experiment. Besides demonstrating how protons can be used to generate wakefields, AWAKE will also develop the necessary technologies for long-term, proton-driven plasma acceleration projects. TRIUMF has joined the collaboration and has identified beam diagnostics as a potential technical contribution. The collaboration will put TRIUMF accelerator physicists at the fore-front of this ground breaking research.

## A.8 Broadening internal capabilities

### A.8.1 New Superconducting RF centre

The current generation of linear accelerators is enabled by the technology of superconducting radio frequency accelerating cavities made of pure niobium. These accelerators cover the whole gamut of installations from future high energy research accelerators such as the International Linear Accelerator, to low energy research machines such as the ARIEL e-LINAC at TRIUMF, free electron lasers and energy recovery linacs (ERLs), and to industrial and clinical machines. Applications using both pulsed and continuous wave (CW) rf operation are being considered and each are pushing the limits of the present technology. Increased accelerating gradients for high energy pulsed machines and increased Q values for low energy CW machines or higher operating temperatures, could lead to dramatic cost reductions. The ISAC-II and e-Linac SRF projects have led to the development of an SRF infrastructure unique in Canada. SRF research and development covers both the fundamental and the practical. A tech transfer to PAVAC industries on SRF technology has led to a partnership that gives TRIUMF a competitive edge in terms of the ability to explore new SRF strategies. In order to fully leverage the SRF investment the SRF infrastructure should be expanded to allow a broader scope of collaboration. Additions include an enlarged clean room, a high vacuum furnace, and a new chemistry lab. The new SRF centre would allow the development of full cryomodule production to support in house projects as well as to allow TRIUMF/PAVAC to participate in large global projects like Chinese ADS and the ILC. In particular components for the front end of a high intensity proton linac would be developed that would have application as a replacement for the 500MeV cyclotron. This machine would not only support ISAC/ARIEL proton driver requirements but also could be used for neutron production, proton therapy and slow muon production for material science.

## A.9 ERL test facility

The ARIEL electron linac has been installed consistent with adding a single pass recirculating ring to allow the linac to run in Energy Recovery Linac (ERL) mode or Recirculating Linac Acceleration mode (RLA). In one case the electrons are fed back through the acceleration section in anti-phase with the accelerating fields so that the energy gain (beam loading) on the first pass is compensated in the second pass through energy loss and hence energy recovery. Several ERL test facilities are being pursued in the world. ERLs hold the promise of becoming the future backbone of modern accelerator facilities, satisfying the needs of the user community in applied science and fundamental research. They combine the efficiency advantage of storage rings with the improved beam quality achievable in a linac. Thus the ERL offers two important properties: an electron beam having high-brightness and high-power capabilities simultaneously. The beam generated by an ERL has the potential to be applied to a large number of uses: particle collider, compact Compton sources and the next generation of synchrotron light sources. With respect to the latter ERLs provide radiation with characteristics that cannot be matched by third-generation storage rings. In the future the dynamics of microscopic, molecular, atomic and subatomic processes must be analyzed on extremely short time scales down to the femtosecond range. Snap-shots of ultrafast processes must become available to investigate the time dependency of structural material transformations. Light sources based on the ERL technology could meet the increasing demands of a growing user community with a focus on the study of dynamic effects. For ERLs, the demands placed on the electron source, the SRF linac, and the beam transport are severe due to the required beam quality, high current and the CW operation. Ultimately, the technology and concepts have to be put to the test in an ERL test facility. The ARIEL e-Linac gives TRIUMF most of the required infrastructure to develop such a test facility. In addition a small user facility can be installed by adding an Infrared Free Electron Laser (IR-FEL) on the back straight as a light source.

### A.9.1 Ultra-high gradient laboratory

In addition to joining the AWAKE collaboration in order to advance the ultra-high gradient initiative in Canada a test facility needs to be developed at TRIUMF. In Laser Wake Field Acceleration (LWFA) strong laser pulses propagating in plasma generate a charge separation through the excitation of wakefields. Wakes with electric fields many orders of magnitude larger than in conventional accelerators are possible. The proposal would be to develop a LWFA test facility at TRIUMF for research and development in a student focused program.

### A.9.2 Accelerator education centre

TRIUMF is Canada's centre for accelerator science. In the last several years TRIUMF has organized a Accelerator Physics course offered through UBC and U. Victoria. Ten graduate students are presently registered in Accelerator Physics projects at TRIUMF and this number is growing as more students and associated universities see the benefit of the expertise and infrastructure at TRIUMF for the training of HQP. We propose to grow the program with the addition of key hardware to form an accelerator study centre. The infrastructure would include a small student designed cyclotron, a small electron ring a diagnostic test facility and an ion source test stand with analyzing station.