Canadian Subatomic Physics
LONG-RANGE PLAN

2022–2026

WITH AN OUTLOOK TO 2036

REPORT

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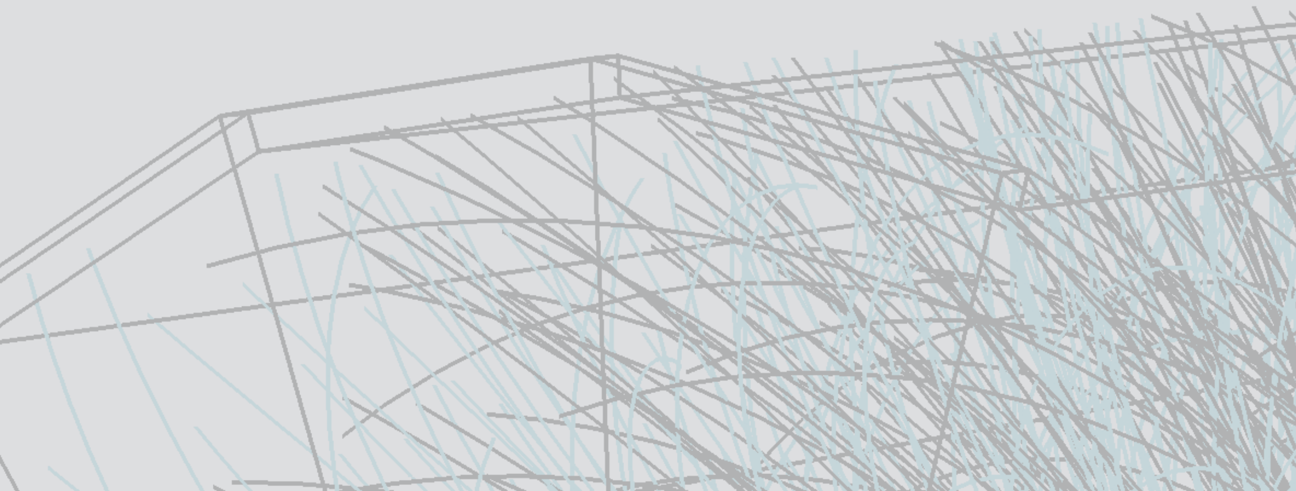

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Executive Summary

SUBATOMIC PHYSICS

is a fundamental science that seeks to understand the basic building blocks of the universe and the laws that explain the behaviour of those constituents.

OVER THE PAST CENTURY, the global subatomic physics community has developed an increasingly detailed understanding of this realm, culminating in the development of the Standard Model of particle physics. This theoretical framework unifies electromagnetism, the strong force that binds protons and neutrons, and the weak forces that control neutrinos and nuclear decay. The ongoing development of this theoretical framework most recently led to the discovery of the Higgs boson in 2012. While remarkable progress has been made in this field, many deep questions remain. Future goals include identifying the nature of dark matter and the origin of neutrino mass, explaining how nuclear structure emerges from the theory of quarks and gluons, and improving our understanding of quantum mechanics and relativity to uncover the basic structures underlying matter and the fundamental forces.

The development of our collective knowledge in subatomic physics is a collaborative global endeavour, involving a synergy between advanced theoretical work, cutting edge computational analysis, and experiments which utilize some of the most sophisticated machines ever devised, such as the Large Hadron Collider at CERN. Within this global community, Canadian subatomic physics has an enviable reputation, with leadership and impact on many of the major projects that have advanced our understanding in recent decades. In particular, Canadian researchers have played leading roles on experimental projects connected with recent Nobel Prize awards for the discovery of the Higgs boson and the discovery of neutrino flavour change.

Over the past five years, Canadians have taken on significant roles in national and international experiments, ranging from substantial involvement in the ATLAS experiment at the LHC, to a variety of strategic efforts on projects at world-class Canadian and international facilities. The focus of these projects has been to test neutrino properties and search for dark matter, test the structure of protons, neutrons and increasingly complex nuclei, and to perform a variety of precision tests of fundamental symmetries and foundational properties of the Standard Model. Canada is also uniquely positioned to play a major role in the future development of this international field, hosting the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, and two world-class experimental facilities, the SNOLAB deep underground laboratory in Sudbury, Ontario, and TRIUMF, Canada's particle accelerator centre in Vancouver, BC. The Canadian community has pursued projects at these domestic facilities, and has also strategically invested in international laboratories that provide world-leading and complementary infrastructure.

Investment in subatomic physics research leads to returns that are multi-faceted. In addition to expanding our collective understanding of nature, the field provides inspiration and a rich and unique training ground for students and research personnel. In addition to the core skills in problem solving that are typical of physics education, the highly collaborative nature of subatomic physics research also provides trainees with valuable "soft skills", and the strong synergies between subatomic physics and other fields, including astronomy and cosmology, materials science, quantum technologies, and high-performance computing, provide many opportunities for cross-disciplinary research. Subatomic physics research also drives the development of technology, with spin-off developments now important in many areas such as health care, energy, and computing.

The impact of the Canadian subatomic physics community in recent years has been bolstered by collective organization, and cohesive effort on carefully identified projects with significant science outcomes. The Subatomic Physics Long-Range Plan Committee, in consultation with the Canadian subatomic physics community, has developed a roadmap for continued success over the period 2022–2026, with an outlook to 2036. The research plan follows from the same guiding principles that have supported past success:

- tackle the most important research problems in the field;
- maximize impact by concentrating effort and taking on leadership responsibilities in select major projects, while strategically engaging in a range of smaller-scale projects with the potential for high reward;
- maintain flexibility to adjust to new scientific advances; and
- fully engage an increasingly diverse population of students and postdocs in all aspects of research, and support their career development.

The scientific drivers for subatomic physics research, and the associated opportunities, can be structured around three broad science directions:

BROAD SCIENCE DIRECTION —
From quarks and gluons to nuclei.
Canada's TRIUMF Laboratory, with its Advanced Rare Isotope Laboratory (ARIEL) upgrade and associated suite of targets and experiments utilizing rare isotope beams, presents an opportunity for Canada to continue its leading role in mapping out nuclear structure and properties. In addition, strategic investment in new and complementary offshore facilities in US and Europe will broaden research capacity.

BROAD SCIENCE DIRECTION —
Matter in the weakly coupled universe.
Seeking the identity of dark matter in the universe, and the underlying properties of neutrinos is a growing area of focus worldwide. Canada is very well-positioned to continue its central role in this international effort, with the SNOLAB underground facility in Sudbury currently hosting a variety of world-leading experiments and being well-placed to take a leading role in next generation searches. Canada is also actively involved in major international neutrino experiments.

BROAD SCIENCE DIRECTION —
Beyond the electroweak energy scale.
The Canadian community is well-positioned to explore the high energy frontier through its long-standing involvement in international particle collider projects in Europe and Japan, and strategic involvement in smaller-scale precision experiments. In addition, Canada's TRIUMF Laboratory has the opportunity to position itself as a world-leading facility for future high-precision tests of physics at the energy frontier using rare isotopes. Canada is also poised to take a significant role in the development of the next generation of particle colliders.

Theoretical work by Canadian subatomic physicists on all of these themes is critical to future progress. This includes work that is closely tied to analysis and interpretation of experiments, and also fundamental theory that seeks the new ideas that will explain existing puzzles and shape our understanding of subatomic physics in the future.

A number of external and internal sources of support will be required for the subatomic physics community to take full advantage of these opportunities for Canada. Moderate but critical increases to operational funding via the NSERC subatomic physics envelope, and continued access to capital funding at current levels for new experimental projects via CFI, are required.

Substantial and stable funding is also necessary to maximize the impact of Canada's unique world-class facilities: SNOLAB, TRIUMF, and the Perimeter Institute. Computing and network infrastructure is critical to this field, and Canada's new Digital Research Alliance (formerly NDRIO) and CANARIE are vital components of the subatomic physics research ecosystem. Funding opportunities to develop enabling and emerging technologies are also critical in support for future research projects. Maintaining support for Canada's Institute of Particle Physics (IPP) Research Scientist Program is a high-priority for the community. In addition, initiatives developed and run by the Arthur B McDonald Institute have added considerable value to the subatomic physics ecosystem in Canada. At the governmental level, future scientific developments would be greatly facilitated by the existence of high-level national structures to coordinate costs for large-scale science endeavours, and to aid international engagement in multi-national projects. Finally, achieving a more equitable, diverse and inclusive Canadian subatomic physics community is vital to ensure research excellence and that the societal benefits stemming from subatomic physics research are equitably distributed. Sustained efforts by individuals and organizations to improve equity, diversity and inclusion need to encompass training, career development and outreach.

The subatomic physics community in Canada has achieved great success, and is well-positioned to take on future challenges in unlocking the secrets of fundamental physics at the subatomic scale. The Long-Range Plan for 2022–2026 is described in detail in this report, with the key action items, some of which were highlighted above, expressed in a series of recommendations on Science, Funding, Policy, and Community.

Recommendations

SCIENCE RECOMMENDATION
1 — CANADIAN INFRASTRUCTURE

We recommend fully capitalizing upon the unique science opportunities provided by the SNOLAB and TRIUMF infrastructure, and by the Perimeter Institute, in pursuit of the science drivers.

SCIENCE RECOMMENDATION
2 — THEORY PROGRAMS

Critical mass and research breadth are vital for the theory community in Canada, to maximize the future impact of subatomic physics research. We recommend strong support for theoretical subatomic physics research over the next decade, both to explore new purely theoretical directions and to support the synergistic interaction between subatomic theory and experiment.

SCIENCE RECOMMENDATION
3 — **EXPERIMENTAL PROGRAMS**

A broad experimental program is required to address the scientific drivers of subatomic physics research. We recommend pursuit of the following high-priority scientific directions.

- **FROM QUARKS AND GLUONS TO NUCLEI** — *The future program should explore the structure of hadrons and nuclei using rare isotope and accelerator-based facilities. It should include the full exploitation of TRIUMF, offshore electron beam and rare isotope beam (RIB) facilities, and a future electron-ion collider.*

- **MATTER IN THE WEAKLY COUPLED UNIVERSE** — *The future program should incorporate the search for dark matter using complementary direct and indirect techniques, including via multi-ton scale direct detection. The future program should include the further exploration of neutrino properties via neutrinoless double-beta decay experiments, long baseline experiments and neutrino observatories.*

- **BEYOND THE ELECTROWEAK ENERGY SCALE** — *The future program should study matter and its interactions at increasingly higher energy scales, including the exploitation of a future Higgs factory and energy frontier collider, as well as high-precision indirect techniques.*

This scientific program is currently implemented through Canadian leadership in a set of flagship projects identified based on their potential scientific payoff, Canadian core expertise, the level of community engagement, opportunities for the scientific and technological training of the next generation, and Canadian investments to date:

	Flagship projects with broad physics outcomes	***Flagship projects with strategic physics outcomes***
FROM QUARKS AND GLUONS TO NUCLEI	TRIUMF ARIEL-ISAC experiments, EIC	JLab 12 GeV program, Offshore RIB experiments
MATTER IN THE WEAKLY COUPLED UNIVERSE	T2K/HK, IceCube, SNO+	DEAP, PICO-500, SuperCDMS
BEYOND THE ELECTROWEAK ENERGY SCALE	ATLAS(LHC/HL-LHC), Belle II	ALPHA/HAICU, MOLLER, TUCAN

We recommend the support of these projects and also those initiatives within the scientific program, with the potential for high impact, that are under development or may be developed in the coming years. Potential future projects with ongoing development activities and their timelines are listed in the research portfolio presented in FIGURE 4.

SCIENCE RECOMMENDATION
4 — **R&D ACTIVITIES**

We recommend the support of R&D activities for the future development of particle accelerators and detector technology, and the development and use of emerging technologies including novel computational and analysis tools.

COMMUNITY RECOMMENDATION
5 — **EQUITY, DIVERSITY & INCLUSION**

The Canadian subatomic physics community lacks diversity, as do some other science and technology fields. This lack of representation has many causes, and spans the full career range from graduate students to senior faculty. It is widely recognized that diversity is valuable for the research enterprise, and that a lack of diversity in itself creates a barrier to entry into the field.

- *We recommend the pursuit of further sustained actions aligned with the Tri-Council Dimensions Charter, including regular data-gathering and analysis, targeted initiatives to enhance equity, diversity and inclusion within community activities, and community use of formal committees through the Institutes to support these efforts and/or coordinate with partners.*
- *We recommend that the subatomic physics community promote balanced representation in high visibility leadership roles, as individuals in these positions are important role models, while recognizing that achieving adequate representation can increase the workload for members from under-represented groups.*
- *We recommend that the subatomic physics community promotes inclusion through acknowledgement of the legacy of colonization in Canada, e.g. with the use of land acknowledgements at events held in Canada, consistent with the spirit of the Calls to Action of the Truth and Reconciliation Commission of Canada and of the United Nations Declaration on the Rights of Indigenous Peoples.*

COMMUNITY RECOMMENDATION
6 — **TRAINING & CAREER DEVELOPMENT**

To enable highly qualified personnel to receive training that makes use of the national collaborative structure of subatomic physics research, we recommend the coordination and sharing of training opportunities across Canadian centres, institutes, and universities.

To support early career development, we recommend that Early Career Researchers be supported to quickly gain knowledge of the Canadian subatomic physics research support and funding ecosystem, and be given opportunities to interact broadly with the community.

COMMUNITY RECOMMENDATION
7 — **COMMUNICATION & ENGAGEMENT WITH AGENCIES & GOVERNMENT**

We recommend the formalization (e.g. by CINP and IPP) of a subatomic physics consultation committee for engagement and advocacy to funding agencies and government.

FUNDING RECOMMENDATION
8 — **CFI PROGRAMS**

Support for the development of capital infrastructure through CFI has been instrumental for the development of subatomic physics research in Canada. We recommend continuation of this investment at current annualized levels, which will be critical for the success of the Canadian subatomic physics research plan including many of the proposed future initiatives.

FUNDING RECOMMENDATION
9 — **NSERC SUBATOMIC PHYSICS ENVELOPE**

To maximize the impact of current and future investments, and to take advantage of future science opportunities, growth of the NSERC subatomic physics envelope is required for operational support.

- *We recommend retention of the NSERC subatomic physics envelope structure, and its programs, which have been instrumental for the operational funding of subatomic physics research.*
- *We recommend growth of the NSERC subatomic physics envelope by $6.2M in 2021 dollars over the next five years to ensure that the Canadian program remains globally competitive. This growth is required for several reasons: to accommodate the transition of McDonald Institute faculty requiring NSERC support; to utilize the full community capacity for training of highly qualified personnel and maximize the return on capital investment; and to ensure sufficient availability of funds for small infrastructure projects and the development of future science opportunities.*
- *We recommend continued support for all the program categories available within the NSERC subatomic physics envelope; this includes the Major Resources Support (MRS) program, which critically supports the efficient collaborative use of unique technical resources in the development and construction of new instruments, and the Research Tools and Instruments (RTI) program which provides important support for detector and accelerator development.*
- *We recommend the monitoring and protection of the NSERC subatomic physics envelope fraction allocated to fund theory investigators. In addition, the minimum award threshold should not be below the level of funding required to support graduate training, as is the case in other Physics Evaluation Sections.*

FUNDING RECOMMENDATION
10 — **SUPPORT FOR CANADA’S WORLD-LEADING CENTRES**

Canada’s large-scale centres for subatomic physics research have global stature, and provide competitive advantages in pursuing high-priority scientific programs.

We recommend maintaining strong support for Canadian centres (TRIUMF, SNOLAB, Perimeter Institute) so that they remain at the forefront of research worldwide.

FUNDING RECOMMENDATION
11 — **IPP RESEARCH SCIENTIST PROGRAM**

The IPP Research Scientist program has had a major impact on Canada's leadership and contributions to international projects.

We recommend maintaining full support for the IPP Research Scientist program.

FUNDING RECOMMENDATION
12 — **ARTHUR B MCDONALD INSTITUTE**

The existence of the Arthur B McDonald Institute and its research support and outreach programs has added considerable value to the community. However, its CFREF funding is coming to an end.

We recommend that in addition to growth of the NSERC subatomic physics envelope to support operational costs, new mechanisms be identified to fund and maintain continuity of the research and technical support programs provided by the Institute.

FUNDING RECOMMENDATION
13 — **CANADA'S DIGITAL RESEARCH INFRASTRUCTURE**

All components of digital research infrastructure (e.g. Compute Canada, CANARIE) are critical to the success of subatomic physics research.

We recommend that CANARIE continues to be funded by the Canadian federal government for operation of the national research network and key links to our international partners. Further, we recommend that critical computing infrastructure provided by national computing organizations (Compute Canada and the Digital Research Alliance (formerly NDRIO)) continue to be strongly supported by federal and provincial governments, at a level appropriate to address the needs of the subatomic physics research community.

FUNDING RECOMMENDATION
14 — **FUNDING FOR R&D ACTIVITIES**

New research opportunities are enabled by the development of novel instruments and technologies. This development relies upon the ability to explore technological frontiers that are beyond the scope of individual subatomic physics experiments.

We recommend that appropriate mechanisms be identified to efficiently fund modest and timely investments in generic R&D activities that have the potential to address the scientific goals of subatomic physics research.

POLICY RECOMMENDATION
15 — **SUPPORT FOR LARGE-SCALE SCIENCE ENDEAVOURS**

Coordination of the capital costs and operational funding over the life-cycle of large-scale ($\gtrsim$ $50M) science endeavours and infrastructure projects is difficult within the current ecosystem.

We recommend the formation of a new administrative structure to provide this coordination (as articulated in Recommendation 4.7 of Canada's Fundamental Science Review 2017: Investing in Canada's Future*, http://sciencereview.ca).*

POLICY RECOMMENDATION
16 — **CANADIAN OFFICE FOR INTERNATIONAL RESEARCH ENGAGEMENT**

Subatomic physics research is intrinsically global, and increasingly requires complex multinational agreements.

We recommend the identification of an office in Canadian government responsible for engaging with the international community with the goal of advancing major new science initiatives.

THIS PAGE AND FOLLOWING PAGE: Researchers marking the successful completion of the first of two muon New Small Wheels (NSW) for the upgrade of the ATLAS experiment at the CERN laboratory in Switzerland.

The ATLAS experiment enables researchers to study the results of high energy proton-proton collisions produced at the Large Hadron Collider, with the aim of studying the properties of the Higgs boson and mechanism of electroweak symmetry breaking, as well as searching for evidence of new physics phenomena. [Credit: F. Lanni.]


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Introduction

SUBATOMIC PHYSICS aims to understand the nature of the most basic building blocks of the universe and the laws that explain the behaviour of these fundamental constituents. Remarkable progress has been made in this field in recent years, notably with the discovery of the Higgs boson and the elucidation of the properties of neutrinos. Despite these achievements, many deep questions remain which continue to stimulate new research directions.

Canadian subatomic physicists have played an outsized role on the global stage, thanks to the support of government, funding agencies, universities, the Canadian community, and a history of effective self-organization in tackling the major science questions. Research in subatomic physics involves a synergy between advanced theoretical work and computational analysis with some of the most technologically advanced experiments ever devised and constructed. This research field is global, and often involves large international teams of skilled researchers and technicians. This in turn provides unique training opportunities for students and junior research personnel, many of whom move into a variety of areas in the growing knowledge-based economy.

This report, the Canadian Subatomic Physics Long-Range Plan 2022–2026 (LRP 2022), is the latest in a quinquennial series of plans developed to guide the progress of subatomic physics research in Canada. The present planning process was co-commissioned by NSERC, the Canadian Institute for Nuclear Physics (CINP) and the Institute for Particle Physics (IPP). The CINP and IPP community institutes represent the professional nuclear and particle physicists in Canada. The goals of this planning process are articulated in the mandate (see Planning Process section), and include the identification of the critical science questions driving the field with a fifteen year outlook, the associated opportunities for Canada, and the high priority projects that the community can pursue to address the science goals. The Canadian subatomic physics planning process is community-driven and characterized by extensive consultation and community engagement. The aim of the report is to present a realistic and community-supported vision for Canadian subatomic physics over the coming years. The report seeks to also articulate the funding and other technical support needs required to achieve the stated goals and to present opportunities for the community to enhance its processes, inclusivity, training and outreach.

The primary audience for LRP 2022 comprises the funding organizations and Canadian facilities that support subatomic physics research in Canada. This includes the federal department, Innovation, Science and Economic Development Canada (ISED), and associated agencies such as NSERC and CFI, along with provincial organizations and the research centres and universities that support subatomic physics researchers and their students. The report aims to highlight and articulate the subatomic physics community's success, recent achievements, and opportunities and, as such, is also targeted more broadly at government policy makers. In addition, the subatomic physics community itself is an important audience for this report. Finally, high-level components of the report aim to share, with the broader Canadian public, the excitement, knowledge and other societal benefits gained by public support and investment of tax dollars in this field.

The Long-Range Plan Report is structured to provide a status update on the research field in Canada, a description of the research plan and necessary funding and infrastructure supports needed to implement the plan, and a presentation of broader benefits of investment in this field for Canadian society. A reading guide for subsequent sections follows below:

SECTION 1 —
Science Drivers and the Impact of Canadian Work

This section summarizes the global context for subatomic physics research, the drivers for specific sub-fields, and elaborates on Canadian achievements and broader scientific impact since the previous Long-Range Plan.

SECTION 2 —
Canadian Subatomic Physics Research Plan

Based on the scientific landscape presented in Section 1, Section 2 outlines the science opportunities for Canada, and the enabling technology and infrastructure. The research plan is then presented in the form of a multi-dimensional portfolio of high priority projects aiming to tackle the science drivers.

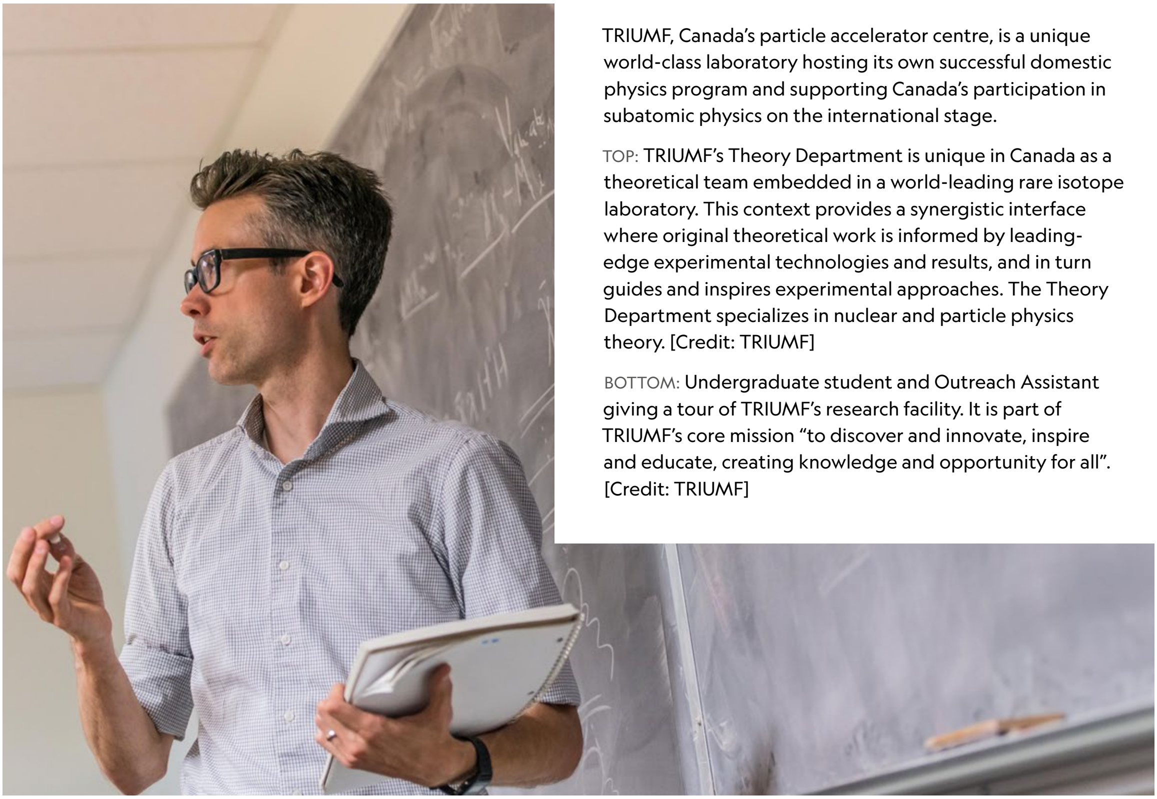
SECTION 3 —
Realizing the Research Plan

This section discusses the various forms of support required to realize the research plan. These are categorized into the broad areas of community actions, funding, technical and infrastructure support, and the broader policy framework.

SECTION 4 —
Benefits to Society

This concluding section takes a broader perspective of the return on investment in subatomic physics research, including the unique training opportunities, the development of new technological applications, commercial spin-offs, environmental impact and opportunities, and the broader cultural benefits of pursuing this most fundamental science.

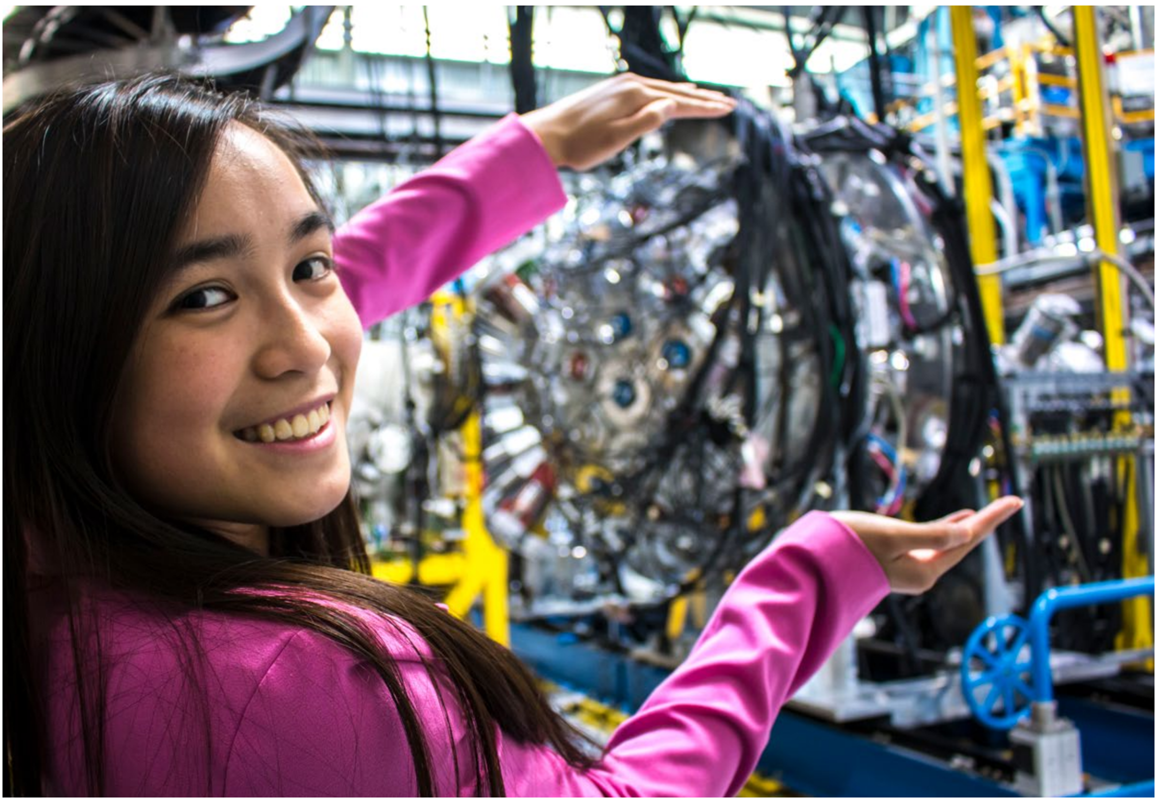
Appendices provide a glossary of acronyms used throughout the report, the governing documents for the planning exercise, and a description of the process followed and extensive community input received by the planning committee. A number of concrete examples of the impact of subatomic physics research, and sample case studies, are distributed throughout the report.



TRIUMF, Canada's particle accelerator centre, is a unique world-class laboratory hosting its own successful domestic physics program and supporting Canada's participation in subatomic physics on the international stage.

TOP: TRIUMF's Theory Department is unique in Canada as a theoretical team embedded in a world-leading rare isotope laboratory. This context provides a synergistic interface where original theoretical work is informed by leading-edge experimental technologies and results, and in turn guides and inspires experimental approaches. The Theory Department specializes in nuclear and particle physics theory. [Credit: TRIUMF]

BOTTOM: Undergraduate student and Outreach Assistant giving a tour of TRIUMF's research facility. It is part of TRIUMF's core mission "to discover and innovate, inspire and educate, creating knowledge and opportunity for all". [Credit: TRIUMF]

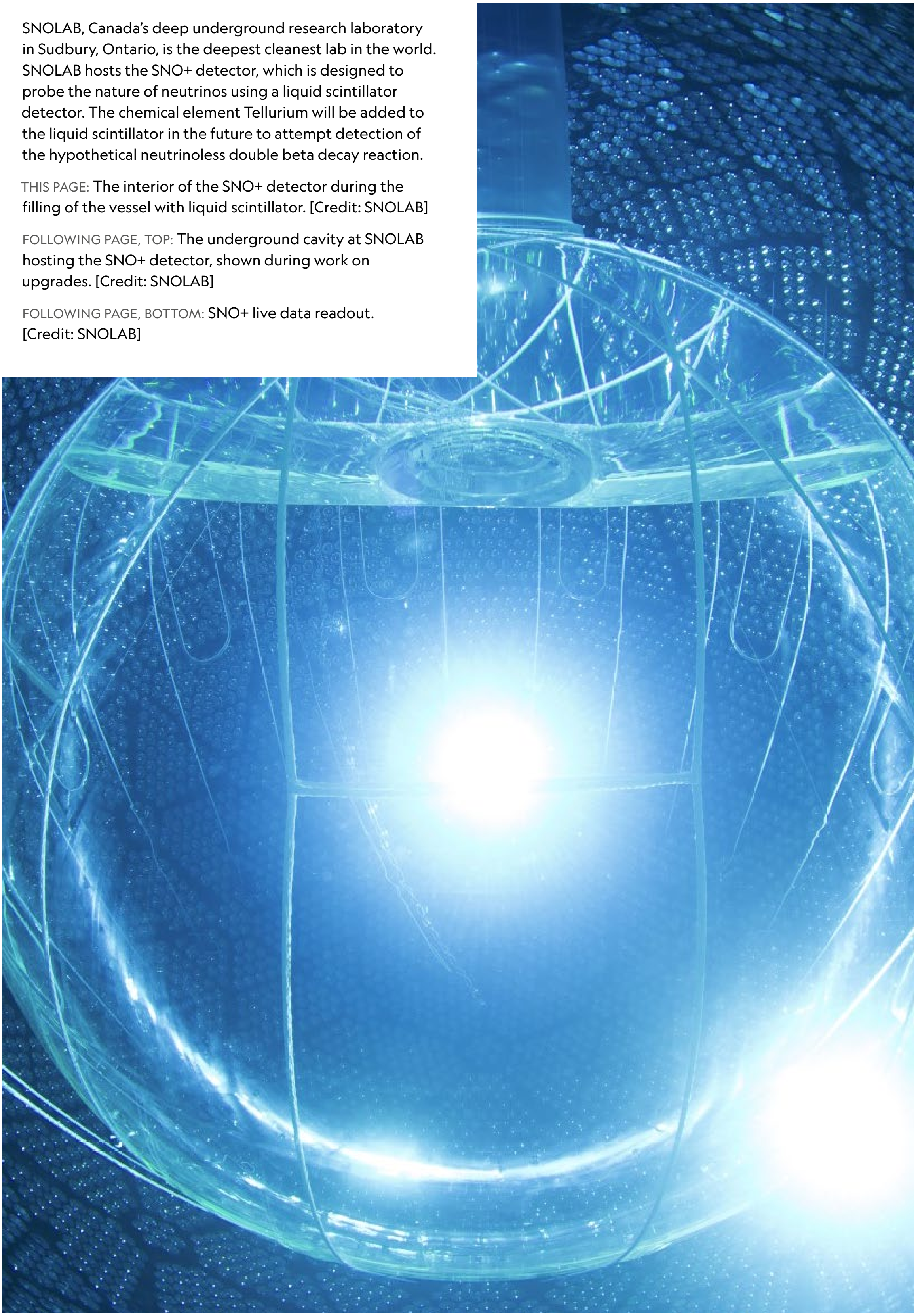


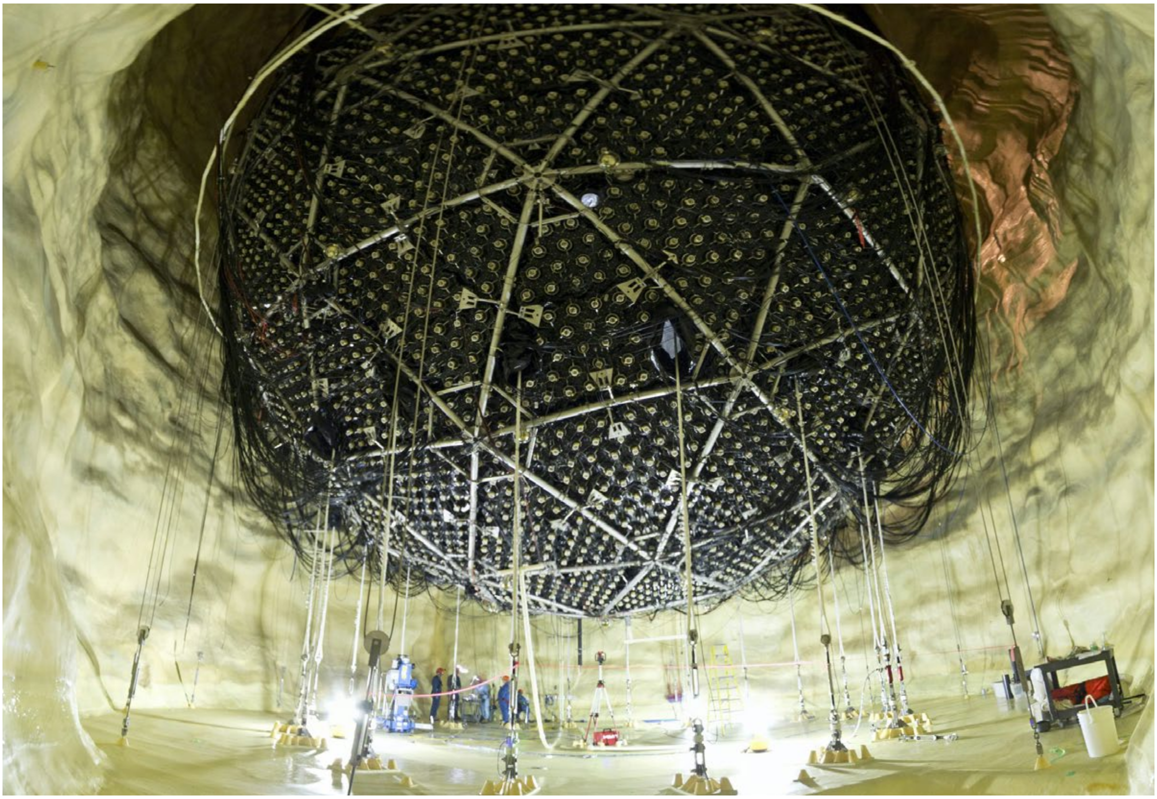
SNOLAB, Canada's deep underground research laboratory in Sudbury, Ontario, is the deepest cleanest lab in the world. SNOLAB hosts the SNO+ detector, which is designed to probe the nature of neutrinos using a liquid scintillator detector. The chemical element Tellurium will be added to the liquid scintillator in the future to attempt detection of the hypothetical neutrinoless double beta decay reaction.

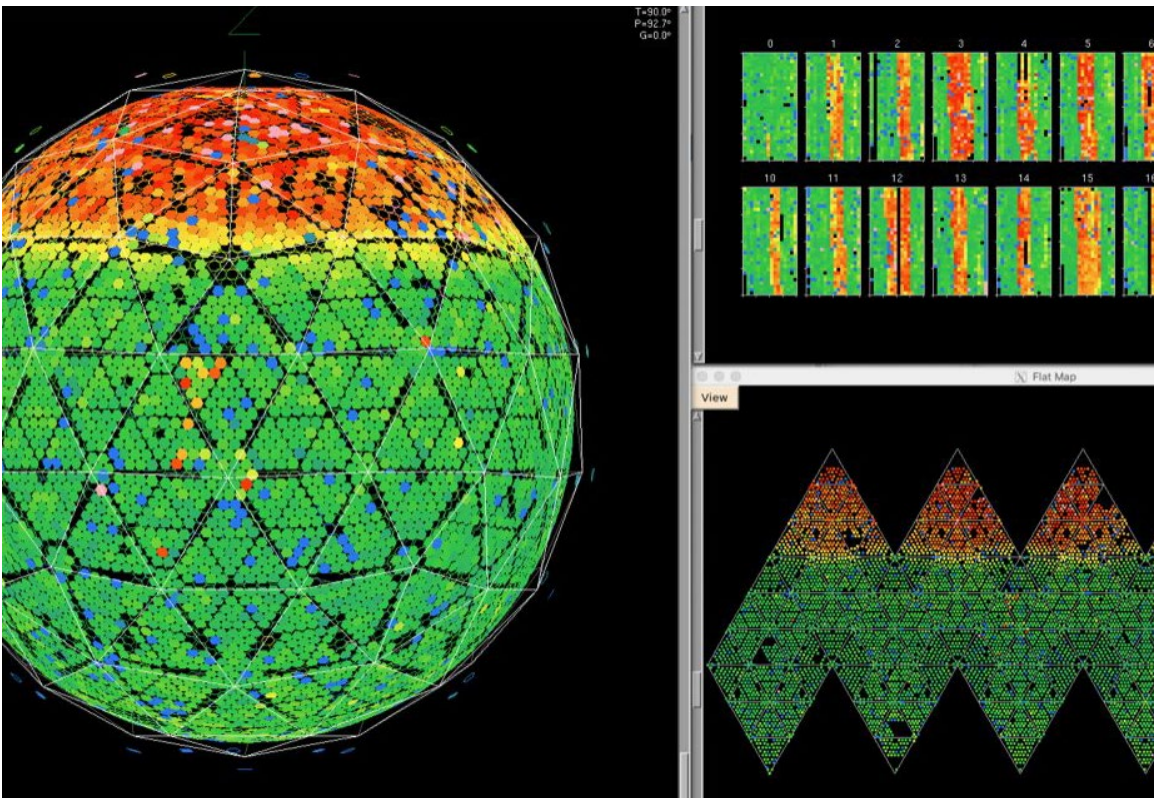
THIS PAGE: The interior of the SNO+ detector during the filling of the vessel with liquid scintillator. [Credit: SNOLAB]

FOLLOWING PAGE, TOP: The underground cavity at SNOLAB hosting the SNO+ detector, shown during work on upgrades. [Credit: SNOLAB]

FOLLOWING PAGE, BOTTOM: SNO+ live data readout. [Credit: SNOLAB]



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Flat Map
View

SECTION 1 – Science Drivers and Canadian Research Impact

THE OVERARCHING goal of subatomic physics is to push the knowledge frontier of what the universe is made of to the very smallest distance scales. In doing so, subatomic physics has been able to distill and translate observations of natural phenomena into universal laws expressed by a few mathematical equations. The existence of this expansive theoretical scaffolding is the very reason specific questions about the universe can be formulated and we can advance systematically in the exploration of the unknown.

The field of subatomic physics research has progressed significantly over the past couple of decades, driven by technological advances, computing power, and theoretical developments. As a prime example, the discovery of the Higgs boson in 2012 at the LHC provided the capstone for the Standard Model of particle physics, yet many questions remain as 'science drivers' for the field and even the Higgs has now become a tool to push forward our understanding of subatomic physics.

The LRP Committee identified eight science drivers for the field of subatomic physics research in 2022 that encapsulate a number of underlying questions:

SCIENCE DRIVER —
Higgs, Physics at the Electroweak Scale, and Beyond

What is the precise nature of the Higgs sector and the flavour sector of the Standard Model? What is the physics of electroweak symmetry breaking? What lies beyond the electroweak scale?

SCIENCE DRIVER —
Fundamental Symmetries and Observed Asymmetries

What are the fundamental symmetries in nature, and how do we explain observed imbalances, e.g. the matter-antimatter symmetry in the universe?

SCIENCE DRIVER —
Neutrino Properties

What is the nature of neutrino mass, the mass hierarchy, and of neutrino interactions?

SCIENCE DRIVER —
Dark Matter and Potential Dark Sectors

What is the nature of dark matter in the universe and its interactions? Is dark matter part of a more extended dark sector?

SCIENCE DRIVER —
New Physical Principles and Structures

A broad range of theoretical questions, including what formal theoretical principles and structures underly the forces and matter in the universe?

SCIENCE DRIVER —
Hadron Properties and Phases

How do quarks and gluons give rise to the properties of nucleons and other hadrons, and to the hadronic phases of matter in extreme conditions?

FIGURE 1. Schematic representation of the three broad science directions and the eight science drivers for the field of subatomic physics research.

SCIENCE DRIVER —
Nuclear Structure

> How does nuclear structure emerge from nuclear forces and ultimately from quarks and gluons?

SCIENCE DRIVER —
Cosmic Formation of Nuclei

> How do the properties of nuclei explain the formation of the elements in the universe?

These science drivers are deeply inter-connected and in combination define three broad science directions in subatomic physics, as illustrated in FIGURE 1. To address the breadth of these science drivers requires a diversified research program of bold projects with complementary objectives, exploiting a variety of different techniques. In the rest of this section, these science drivers are described in more detail, focusing on recent scientific progress as well as Canadian activities and achievements. Indeed, Canadian subatomic physics has an enviable global reputation, with impact on many of the major projects that have pushed our understanding forward in recent decades. The Council of Canadian Academies' 2018 report "Competing in a Global Innovation Economy: The Current State of R&D in Canada" highlights the global impact of Canadian subatomic physics research, as measured by average relative citations which grew from 1.79 to 2.05 compared to the Canadian average of 1.43. Given its global impact, but relatively small community size, physics and astronomy was highlighted in the report as a research opportunity for Canada, and future opportunities and plans will be described in h 3.

SCIENCE DRIVER — Higgs, Physics at the Electroweak Scale, and Beyond

THE DISCOVERY OF the Higgs boson in 2012 identified the remaining missing ingredient in the Standard Model of particle physics. It also identified one of the main agents for the breaking of the fundamental electroweak symmetry in nature. Yet, the electroweak sector remains one of the most puzzling aspects of the Standard Model. The Higgs boson is a type of matter that has never been seen before and its properties are yet to be fully studied. Its mass, for example, is not constrained by any symmetry in the Standard Model, and unlike the mathematical structure of the other forces of nature that are fully specified based on symmetry properties, the addition of Higgs interactions leads to a large number of undetermined parameters in the Standard Model. This makes our current understanding of the role the Higgs boson plays in the universe particularly ad hoc and incomplete, and in stark contrast with the structural simplicity of other aspects of the Standard Model. In particular, this raises the fundamental question of what underlying principles determine the properties of the Higgs boson. This question motivates the possible existence of new physics phenomena beyond those described by the Standard Model, but also identifies the Higgs boson as a unique probe to explore physics processes at and beyond the electroweak energy scale.

Exploration of physics phenomena at and beyond the electroweak scale is taking place in proton-proton collisions at the LHC and will continue in the coming years at the High-Luminosity LHC, through both the measurement of known electroweak processes and searches for signatures of new phenomena. Looking forward, a future electron-positron collider, such as the proposed ILC in Japan or FCC-ee in Europe, would operate as a Higgs factory, producing an enormous number of Higgs bosons, thereby making it possible to measure Higgs properties to an unprecedented level of precision, and possibly uncovering hints of physics phenomena beyond those predicted in the Standard Model.

Precision measurements of physics processes at lower energies also provide a complementary window into new physics at or beyond the electroweak scale. Indeed, the degree of precision of both measurements and Standard Model predictions is an aspect of subatomic physics research that is unique among all the sciences, and can be used to reveal small discrepancies arising due to new physics. This sensitivity can be achieved through the study of rare or forbidden processes in the Standard Model; for example, in the decays of tau leptons, kaons, bottom and charm hadrons, or the study of theoretically well-understood processes such as electron-electron scattering.

Canadian Contributions and Achievements

Canadian researchers have been and continue to be at the forefront of experimental investigations of physics at the electroweak scale and beyond. They hold leadership roles in several different complementary international projects at the energy and precision frontiers located at unique off-shore facilities. Specific achievements of Canadians in the past five years include the following:

The ATLAS experiment is designed to study the results of proton-proton collisions produced by the LHC at the highest energy ever achieved in a laboratory. Canadians have and continue to play a key role in all aspects of this international research program. Major achievements in the past five years include:

- Canadians have directly contributed to the analysis of ATLAS data resulting in the publications of 120 refereed papers on a wide range of topics including the measurement of Higgs boson properties, studies of the electroweak sector, and searches for hints of new physics phenomena.

- Concurrently, the ATLAS-Canada team has also undertaken the development and construction of novel detector elements with significantly improved performance in order to upgrade the ATLAS detector in preparation for HL-LHC data taking.
    - The ATLAS-Canada team has built and delivered to CERN one quarter of all required muon detector elements, and is now completing their integration into ATLAS. These new muon detecting elements will provide the ATLAS experiment with the capability to identify in real-time proton collisions of interest that should be recorded for future detailed offline data analysis.
    - The ATLAS-Canada team has taken on responsibilities for the construction of a new state-of-the-art particle tracking system that will make it possible to precisely reconstruct the trajectory of thousands of charged particles simultaneously created in proton-proton collisions at the HL-LHC.
    - The ATLAS-Canada team is also developing a new electronics readout for the ATLAS calorimeter system that will significantly improve the ability to precisely measure the energy of particles, under the harshest experimental conditions foreseen at the HL-LHC.
- In addition, TRIUMF is developing and will provide crab cavity cryomodules for the HL-LHC as part of a Canadian contribution to the upgrade of the accelerator.

The Belle II experiment at the KEK laboratory in Japan searches for evidence of new physics in a wide range of final states where the Standard Model predictions are well understood. Its physics program is based on the study of a record-breaking quantity of electron-positron collisions at a specific energy enhancing the production of B-hadrons, and is complementary to the LHC physics program. Canadians have been leading the development of key aspects of the Belle II experiment, and are now contributing to its operation. Sample achievements during the past five years include:

- The Canadian team provided beam background shields for the endcap calorimeters which protect the apparatus against the high level of radiation generated from the intense accelerated particle beams. These shields additionally contain monitors used to characterize backgrounds during beam injection to assist in collider operations.
- Canadians developed the reconstruction code for the Belle II calorimeter successfully exploiting the full waveform information to produce significantly better energy resolution in the presence of backgrounds and uniquely providing new hadron identification capability. This contribution positively impacts the entire Belle II program, increasing the overall sensitivity of physics studies.

- The interpretation of collision data requires detailed simulation of known physics processes, for example, to estimate backgrounds. The Canadian team wrote and now maintains the virtual model of the Belle II detector necessary for enabling the entire Belle II physics program.
- Canadians have already started exploiting the new and growing Belle II data set and published timely results in the search for new particles belonging to a possible 'dark sector' in the universe.
- Canadians have been leading the development of the international Chiral-Belle project, a proposal to upgrade the SuperKEKB e^+e^- collider with polarized electron beams. The main goal of Chiral-Belle is to precisely measure the weak mixing angle, a fundamental parameter of the Standard Model, at energy scales complementary to other measurements, to search for evidence of new physics beyond the Standard Model. The Canadian team is leading the study of the accelerated particle beam dynamics around key components of this future accelerator infrastructure; the Spin rotators used to align the polarized electrons at the collision point, and the Compton polarimeter used to continuously monitor the polarisation of the electron beam with high precision.

The NA62 experiment at CERN is designed to measure rare kaon decay branching fractions with high precision. The experiment took data during 2016–2018 and a future data taking period is planned for 2022–2025. Canadians contributed to operational and development activities related to the calorimeter and tracking systems. In the past five years, the Canadian team has focused on the primary objective of the experiment, the measurement of the ultra-rare kaon decay mode $K^+ \to \pi^+ \nu\bar{\nu}$. The decay process is highly suppressed in the Standard Model, yet its probability of occurrence is precisely calculated at the 10^{-10} level. The measurement of this ultra rare decay process provides a unique opportunity to probe for new physics at very high mass scales in a complementary way to searches conducted at the LHC.

The goal of the MOLLER experiment is to make the world's most precise off-resonance measurement of the weak mixing angle, using polarized electron-electron scattering at the Jefferson Laboratory (JLab) in the USA, as a sensitive test for physics beyond the Standard Model. The experiment is under development and scheduled to begin data taking in 2027. Since the last LRP, the Canadian team has made significant progress in leading the design of the magnetic spectrometer and the integrating detectors and associated electronics. The Canadian team has also established leadership roles in simulation and analysis software.

The MoEDAL experiment at the LHC is a dedicated detector array designed to detect magnetic monopoles and other highly ionizing massive particles hypothesized in a number of physics scenarios beyond the Standard Model. During the past five years, Canadians have participated in the experiment's data taking and contributed to the publications of the collaboration's first physics results providing some of the most stringent constraints to-date on the existence of monopoles. Canadians have also led the development, construction and now, current installation of a new detector system to significantly expand the physics program of the experiment during the future LHC Run-3 data-taking campaign.

- The MATHUSLA experiment proposal has been developed during the last LRP period. The proposed experiment is a dedicated large volume detector to be located on the surface above one of the interaction regions at the LHC. The goal of the experiment is to search for neutral long-lived particles hypothesized to exist in various new physics scenarios beyond the Standard Model. Canadians have been instrumental in developing the physics case for this experimental proposal through various sensitivity studies. Canadians have also recently begun to participate in the construction and commissioning of a demonstrator unit and will contribute to the analysis of preliminary data recorded with this demonstrator.

- The development of a future Higgs factory is identified by the international community as a top priority. The ILC is the most advanced and mature proposal on the world-stage that, if approved, would be located in Japan. There are also complementary proposals for electron-positron machines, such as the post HL-LHC Future Circular Collider (FCC-ee) that could eventually be transformed into the next energy frontier hadron machine. In the past 5 years, Canadians have continued to contribute to R&D work for the design of tracking and calorimeter systems, and to improve performance of superconducting radio-frequency (SRF) cavities for a future ILC detector. More recently, Canadians have joined international efforts towards the development of semi-conductor sensor devices that can tolerate very high radiation levels and be used in the design of tracking systems at future colliders. Moreover, TRIUMF is a member of an international collaboration on the development of SRF crab cavities for the ILC. This collective R&D program will build on existing Canadian infrastructure and enable Canadians to take on a central role in a future international collider project.

- The Canadian particle theory community has been active in proposing ways to test whether the Higgs boson discovered in 2012 is the same as the one predicted by the SM using data from the LHC and beyond, and is exploring novel new physics signatures that motivate analyses at colliders.

SCIENCE DRIVER —

Fundamental Symmetries and Observed Asymmetries

PRINCIPLES OF SYMMETRY play a fundamental role in dictating the laws of nature; yet, the full realization of our universe also relies on subtle mechanisms via which symmetry is broken or hidden. As such, precision experimental tests of both observed symmetries and known symmetry violations provide a powerful and complementary approach to the search of new physics phenomena beyond the Standard Model. More specifically, tests of invariance under the discrete transformations of charge conjugation (C), parity (P), and time reversal (T) provide important probes for new physics. Experimental observations have established that the symmetry associated with the individual P and combined CP transformations is violated in nature, and these effects are incorporated in the Standard Model, although their fundamental origin remains unknown. Moreover, the observed magnitude of CP violation in nature is insufficient to explain the predominance of matter over antimatter observed in the universe. Sources of CP (or T) violation due to new physics phenomena can be searched for through a number of different experimental approaches, including: precision measurements of CP violation in Kaon and B-meson decays; searches for CP violation in neutrino oscillations in long-baseline experiments; and searches for the existence of electric dipole moments violating time-reversal symmetry in neutrons, atoms, and molecules. Interestingly, the violation of parity symmetry provides for an extremely sensitive means to study the neutral current weak interaction, which is otherwise generally masked by the dominant electromagnetic processes. As a result, precision tests of the weak interaction can be achieved using parity violating measurements made in electron-electron scattering, electron-proton scattering, atomic systems, and using cold neutrons. Other important tests of symmetry properties of the Standard Model include lepton flavour universality and lepton number conservation, that can be explored in various particle decays and experiments studying the nature of neutrinos. Finally, the combined CPT symmetry, believed to be an exact symmetry of nature, can be tested in spectroscopy experiments using anti-hydrogen atoms, and any observed deviation would imply a breakdown of relativistic quantum field theory.

Canadian Contributions and Achievements

The following describes some of the Canadian contributions and achievements in the past five years related to the exploration of fundamental symmetries.

- ALPHA is an experiment at CERN that aims to test *CPT* symmetry and the universality of gravitational interactions between matter and antimatter using anti-hydrogen spectroscopy. With strong leadership from Canadians, the ALPHA collaboration has produced a series of noteworthy achievements such as a test of anti-hydrogen charge neutrality, the measurement of the anti-hydrogen 1*s*–2*s* transition frequency and a demonstration of anti-hydrogen laser cooling.

- TUCAN is an experiment at TRIUMF that aims to measure the neutron electric dipole moment with unprecedented precision using ultra-cold neutrons. Canadians achieved important milestones in the establishment of this physics program: a new fast kicker magnet was built feeding a new proton beamline with a high-power spallation target, and the first ultra-cold neutrons were successfully produced at TRIUMF and their interactions with superfluid helium characterized.

- The goal of the FrPNC collaboration is to search for evidence of new physics phenomena through the study of neutral-current weak interactions with atomic physics methods. Canadians have successfully established a laser trap facility at TRIUMF and recently achieved a major milestone, the detection of the highly forbidden 7*s*–8*s* transition Francium, paving the way to future parity violation measurements.

- Canadians have used the TRINAT facility at TRIUMF to study the decays of short-lived isotopes produced at ISAC in the search for new physics. The recently added capacity to efficiently optically pump trapped atoms has enabled Canadians to achieve the most precise measurement of the beta decay asymmetry to date using ^{37}K.

- Using cold neutrons produced at the Oak Ridge National Laboratory, Canadians have contributed to the first measurement of parity violation in the neutron-proton and neutron-^{3}He systems, providing the most stringent constraints to date on the weak nucleon-nucleon coupling constants. Following in the footstep of these efforts, Canadians have also participated in the development of the future Nab experiment that will test for physics beyond the Standard Model through the study of cold neutron beta decay. Specifically, Canadians have developed a 30 keV proton accelerator at the University of Manitoba that will be used to characterize the large area silicon detectors used in the Nab experiment.

- Canadians have also made significant progress in the development of experiments capable of testing, and measuring, fundamental symmetries as part of a variety of other research programs such as ATLAS, Belle II, Chira Belle, MOLLER, NA62, T2K, Hyper-K, DUNE, SNO+, nEXO and LEGEND, and experimental programs at radioactive beams facilities. The specific Canadian achievements on each of these projects are presented as part of the descriptions of other science drivers.

A primary motivation for exploring new sources of *CP* violation and lepton number violation is their connection to the matter antimatter asymmetry in the universe. Canadian theorists have been actively analyzing the physics signatures of these potential mechanisms, their associated cosmological implications, and new opportunities for experimental tests.

SCIENCE DRIVER — Neutrino Properties

IN RECENT DECADES, studies of neutrinos have revealed many of the properties of these elusive particles, from the paradigm-changing discovery that neutrinos have non-zero mass to the measurement of the surprisingly large mixing angles between the different neutrino species. Still, there is much to learn. We do not yet know the absolute scale of the neutrino mass which has an important bearing on the impact neutrinos have on the evolution of the universe, which of the neutrino species is the lightest, or even whether neutrinos and antineutrinos are distinct particles. We also don't yet know whether neutrinos violate *CP* symmetry in a way that could help explain the excess of matter over antimatter in the universe.

The most promising experimental approach to determining whether neutrinos are their own antiparticles or not is through the search for neutrinoless double beta decay ($0\nu\beta\beta$). Observation of this lepton number violating process would be clear evidence for physics beyond the Standard Model, and clearly demonstrate that neutrinos are Majorana-type particles and hence potentially obtain their masses in a manner completely independent of the much celebrated Higgs mechanism. The observed rate of $0\nu\beta\beta$ would also constrain the absolute neutrino mass. A number of experiments around the world are searching for $0\nu\beta\beta$ using different technologies and different candidate isotopes. Canada is playing a leading role in this effort as SNOLAB provides an exceptional low background site.

Precision measurements of neutrino oscillations provide the potential for further fundamental breakthroughs. Neutrino oscillation experiments, such as those based on high luminosity neutrino beams, reactor anti-neutrinos, and atmospheric neutrinos, will attempt to determine the neutrino mass hierarchy and CP-violating phase. They will also search for signs of new physics such as the existence of sterile neutrinos and non-standard neutrino-matter interactions.

Neutrinos can also act as 'messengers,' providing to us otherwise inaccessible information about such things as supernova explosions, the composition of the interior of the Earth, the solar core, and high energy particle acceleration processes in the cosmos. Such natural neutrinos also provide an opportunity to study the properties of neutrinos and search for beyond-the-standard model physics.

Canadian Contributions and Achievements

Canadian researchers are at the forefront of experimental investigations into the properties of neutrinos. Specific achievements of Canadians in the past five years include the following:

- The Canadian-led SNO+ experiment at SNOLAB will search for $0\nu\beta\beta$ in ^{130}Te. It will also contribute to neutrino oscillation studies through measurements of reactor anti-neutrinos and low energy solar neutrinos. Significant milestones in the development of this research program have been achieved. The SNO+ experiment began operation in 2017 with a water-fill phase and, after a successful data-taking run with water, the transition of the detector to a scintillator fill was completed in 2021.

- The goal of the EXO-200 and proposed future nEXO experiments is to search for $0\nu\beta\beta$ in xenon. The EXO-200 experiment concluded its operation in 2018 at the Waste Isolation Pilot Plant (WIPP) in New Mexico. Canadians have played a leadership role in both the operation of the detector and subsequent data analysis, achieving sensitivity similar to the most sensitive searches and finding no statistically significant evidence for $0\nu\beta\beta$. In parallel, Canadians have contributed to the development of the next generation nEXO experiment, to possibly be sited at SNOLAB, and have taken responsibility for the delivery of key components of the detector such as the outer detector muon veto, water circulation and assay systems and photon sensor testing.

- LEGEND is a program of $0\nu\beta\beta$ experiments based on ^{76}Ge. There is the potential that the proposed future LEGEND-1000 experiment could be located at SNOLAB. A small effort on this research program has recently been established in Canada with contributions initially focused on the development and characterization of specialized germanium sensors.

- The T2K experiment is an ongoing long-baseline neutrino experiment in Japan. Canadians have played an active role in this experiment at all stages, contributing to multiple aspects of construction and analysis, with their work culminating in the publication of the first significant constraint on the neutrino CP-violating phase, a result which is having a profound impact on the community at large and the planning for the next generation of oscillation experiments.

- The future Hyper-K project in Japan builds on the successes of the T2K experiment with construction of an eight times larger far detector and upgrades to the J-PARC beam intensity to build a world-leading neutrino experiment. The Hyper-K project was approved and construction of the detector began in 2020. Canada has taken a leading role in Hyper-K since its conception. The Canadian team's recent activities have focused on various initiatives aimed at suppressing sources of systematic uncertainties that may ultimately limit the precision of Hyper-K measurements. For example, Canadians have led the proposal for a new hadron production experiment to gather hadron interaction data in phase space regions relevant to Hyper-K measurements. Canadians developed the concept of moving the near detector to different off-axis positions to sample different neutrino energy spectra. Canadians have also been leading a proposed test experiment at CERN to establish the detector technologies, calibration methods and detector models of the intermediate water Cherenkov detector necessary for percent level neutrino differential cross-section measurements.

- The future DUNE experiment, at the Sanford Underground Research Facility (SURF) in South Dakota, will study neutrino oscillations using an artificial neutrino beam, as well as atmospheric, solar and supernova neutrinos. Canadian participation in the DUNE experiment has recently been established with contributions around the following key areas of the physics program: near detector commissioning, development of the data acquisition, trigger and calibration systems, and development of the DUNE computing model.

- IceCube is a high energy neutrino telescope sited at the South Pole. In addition to studies of ultra-high energy neutrinos, IceCube also makes significant contributions to the precision measurement of mixing parameters at high energy. Canadians have established leadership in key data analyses such as atmospheric neutrino fluxes and oscillations, supernova neutrinos, indirect dark matter searches and tests of Lorentz invariance. Additionally, Canadians have been playing an active role in the development and use of new optical modules that will be deployed as an extension to IceCube to enhance the angular resolution of high-energy neutrino events. This IceCube upgrade work pursued by Canadians will have an extensive synergy with the work required to develop similar trigger and reconstruction algorithms for the future P-ONE detector, which will use almost identical optical modules used in the IceCube upgrade. Indeed, Canada is preparing to take on a major role with P-ONE off the coast of Vancouver Island, BC, a project that would utilize the CFI MSI-funded Ocean Networks Canada infrastructure to expand the global capabilities and sky coverage of neutrino telescopes.

- HALO is a Canadian-led supernova neutrino experiment operating at SNOLAB. The Canadian team has extended its leadership to the development of the proposed HALO-1kT experiment that would be sited at the Laboratorio Nazionale del Gran Sasso (LNGS) in Italy. HALO-1kT is a detector of opportunity being pursued because of the availability of 1000 tonnes of lead from the decommissioning of the OPERA experiment.

- The BeEST experiment aims to perform the highest-sensitivity search for keV-scale sterile neutrinos to date using the electron capture decay of ^{7}Be implanted into superconducting quantum sensors. Canadians have contributed to the publication of the first limits with this technique. These new constraints improve upon previous decay measurements by up to an order of magnitude.

- The coherent elastic neutrino-nucleus scattering process provides a clean environment to search for new physics and is also astrophysically important, playing a role in supernova processes and their detection. Canadians are involved in a number of experiments studying, or planning to study, coherent elastic neutrino-nucleus scattering using different types of target nucleus. These include COHERENT, Scintillating Bubble Chamber (SBC), NEWS-G, MINER and RiCOCHET.

SCIENCE DRIVER —

Dark Matter and Potential Dark Sectors

COMPELLING DATA FROM galactic rotation curves, the dynamics of galaxy clusters, the large scale structure of the universe, and the cosmic microwave radiation demonstrates that ~ 85% of the matter in the universe today is non-baryonic dark matter. Furthermore, neutrino measurements and large-scale structure indicate that only a small fraction of dark matter can be in the form of neutrinos. A global experimental and theoretical effort is testing many hypotheses concerning the nature of dark matter, including thermal relics from the early universe, a category which includes weakly interacting massive particles (WIMPs), and a range of theoretically motivated lighter mass scenarios such as axions, sterile neutrinos, dark photons, and other dark sector degrees of freedom including the mediators of new forces through which dark matter may interact.

Experiments can search for dark matter in at least three ways: through direct detection of ambient dark matter in the galactic halo, production and detection in accelerator-based experiments, and through observation of dark matter annihilation signatures.

Direct searches for dark matter candidates are carried out in large ultra-clean underground observatories or through their possible interactions with strong magnetic field. The most sensitive searches for high-mass WIMPs use noble liquids as a target while direct searches for low-mass WIMPs use a variety of techniques and materials including searches for scattering off electrons. Searches for WIMPs interacting with nucleon spin use targets such as fluorine. The direct searches for axions, on the other hand, typically rely on the possible axion-to-photon conversion that could take place in a strong magnetic field such as that present in a resonant cavity or in the vicinity of a nucleus in a target material.

Dark matter particles and particles related to a possible dark sector could be produced in accelerator-based experiments in particle collisions or beam dump experiments. The strategy with this experimental approach is to search for visible or invisible decays of a dark mediator particle that would couple to both dark matter and known Standard Model particles.

Indirect searches for dark matter are also carried out by astronomical observatories looking for signatures of dark matter annihilation, including cosmic rays and neutrinos.

Canadian Contributions and Achievements

The presence of SNOLAB gives Canada a prime position from which to take a leading role in the direct search for dark matter. Canadians have been particularly productive in the past five years and the following list highlights some recent achievements.

- The Canadian-led DEAP-3600 experiment uses a large liquid-argon detector at SNOLAB to search for high-mass WIMPs. It has been in operation since 2017 and successfully demonstrated the very low background levels achievable in liquid argon, based in part on the use of advanced pulse-shape discrimination techniques. The DEAP-3600 collaboration has published the best dark matter limits in liquid argon; these are complementary to limits obtained with other target materials. Canadians have also contributed to the interpretation of these limits in the context of effective field theories and the velocity distribution of dark matter given uncertainties in galactic dynamics.

- The Canadian-led PICO bubble-chamber program at SNOLAB employs superheated fluorinated targets to search for spin-dependent WIMP-nucleus interactions. The PICO-40 detector is in operation and the PICO-500 detector is under construction. The PICO collaboration has published the most stringent direct-detection constraint on the WIMP-proton spin-dependent cross-section.

- The SuperCDMS experiment, which is currently being deployed at SNOLAB, will use germanium and silicon detectors to search for low-mass WIMPs. Canadians have contributed significantly to the analysis of the data taken during previous deployments at Soudan Mine, USA and the resulting publications of the results of detectors operating with a high-voltage bias, exploiting the Luke-Neganov effect. This work forms the basis of the deployment of SuperCDMS-SNOLAB. In addition, the Canadian Cryogenic Underground Test Experiment (CUTE) at SNOLAB has been built and commissioned which will allow for thorough pre-testing of crystals before deployment in SuperCDMS-SNOLAB and for early dark-matter results.

- Canadians researchers have contributed to the publication of a joint analysis with the IceCube and Antares neutrino observatories searching for dark-matter annihilation in the centre of the Milky Way galaxy. While no excess over the expected background is observed, these limits present an improvement of up to a factor of two in the relevant dark matter mass range with respect to the individual limits published by both collaborations.

- The Canadian-led NEWS-G experiment at SNOLAB searches for low-mass WIMPs using spherical proportional counters filled with light atomic mass gases, such as neon, methane, and helium, and thus features particular sensitivity to low mass WIMPs. Canadians have contributed to the publication of the first dark matter search results with a spherical proportional counter at the Laboratoire Souterrain de Modane in France. At the time of publication, the results set new constraints on the spin-independent WIMP-nucleon scattering cross-section for WIMP masses under 0.6 GeV. Canadians have also been significantly contributing to the installation and commissioning of the experiment at SNOLAB that will operate shortly.

- Canadians initiated and developed the new SBC international collaboration for the development of a scintillating bubble chamber that will combine the scintillation of noble liquids with the rejection of electromagnetic backgrounds found in bubble chambers, to search for low mass WIMPs. Canadians have been involved in the development of all aspects of the experiment.

Canadian theorists have been actively involved in developing models for dark matter over the full mass range, studying a range of astrophysical and terrestrial constraints, and have proposed many novel ideas for direct and indirect detection.

SCIENCE DRIVER –

New Physical Principles and Structures

THEORETICAL PHYSICISTS ARE driven to explore fundamental questions about the structure of relativistic quantum field theory itself, the foundation that underlies the Standard Model (SM) of particle physics. These questions cover a particularly wide scope and have the ambitious goals to understand the ultimate nature of physics at high energies, and the unification of particle physics with gravity.

While the SM is a remarkable scientific achievement, and a high degree of quantitative control has been achieved in a number of regimes, a full understanding of its quantum field theoretic building blocks has yet to be achieved and there are mysteries to be understood. Examination has revealed surprising connections, e.g. dualities, between seemingly unrelated theories leading to new calculation techniques at both weak and strong coupling. Important recent progress in the study of strongly-coupled field theory has involved the so-called conformal bootstrap approach, where analyticity and unitarity constraints are used to extract information about quantum field theories even in the absence of a traditional perturbative expansion. Lattice gauge theory is a more direct approach to understanding strong dynamics in gauge theories and Quantum Chromodynamics (QCD) in particular, and is also the subject of considerable theoretical development, e.g. to understand chiral fermions, and indeed as a potential application for quantum computing. Another focus of recent research has been the study of scattering amplitudes, yielding new insights into underlying geometric structures and possibly even the nature of spacetime as well as practical methods for doing calculations in QCD and gravity. Notably, many of these approaches rely on deep and growing links between the formal and the phenomenological approaches to particle theory.

Developing a consistent and complete understanding of gravity at the quantum level remains one of the grand challenges in physics. String theory provides a theoretical framework which accommodates both classical general relativity and quantum mechanics, but is a rich mathematical structure and its concrete application to subatomic physics remains less clear. Most recently exploration of string theory has been productive in elucidating many nontrivial aspects of and connections between quantum field theory, QCD, condensed matter physics, black holes, spacetime, quantum information, and formal mathematics. Perhaps the most far-reaching and nontrivial structure to emerge in this way is the AdS/CFT correspondence or holography, which ties together theories of gravity with quantum field theories in lower dimensions. This discovery nearly 25 years ago continues to stimulate a vast body of theoretical work touching on strong dynamics in quantum field theories relevant to particle and condensed matter physics, thermal dynamics, hydrodynamics and the quark-gluon plasma, and black holes. In recent years, this approach to thinking about the (quantum) physics of black holes has led to new connections to quantum information theory and quantum computing, and new insights about Hawking radiation and a possible resolution of the information loss paradox. Some of these new ideas can be formulated in the traditional language of gravitational path integrals, pointing once again to the power of this dual perspective to provide a novel and productive viewpoint on deep puzzles in conventional physics. Beyond gravity itself, the internal consistency of string theory has provided pointers for where to look for new physics beyond the SM. For example, extra dimensions constitute a new viewpoint from which to consider the sensitivity of the electroweak scale to quantum corrections and the origin of the flavour symmetry structure in the SM.

The synergy between particle physics and early cosmology also provides fertile ground for formal theoretical research that seeks to understand the very early universe. Current cosmological data requires an early epoch of inflation or an alternative description that produces the large scale features observed today and the origins of structure. A full theoretical understanding of early cosmology, and its initial conditions, remains an active research area and one of the few areas where very high scale subatomic physics may leave observable imprints. Indeed, the origins of structure may give us clues to the particle nature of dark matter, while evidence for inflation can provide knowledge about the very high energy structure of subatomic physics. Various early universe scenarios also lead to new predictions, such as the formation of primordial black holes, phase transitions, or topological defects, that are now topical as potentially observable sources of gravitational waves. Finally, understanding the nature of dark energy, and/or the small size of the cosmological constant, remains another grand challenge under study that lies at the intersection of quantum field theory and gravity, and may be a window to understand other deep aspects of fundamental physics.

Canadian Contributions and Achievements

The Canadian formal theory community has actively contributed to, and indeed provided leadership for, many of the topical directions of research progress outlined above. Specific examples of developments since the last LRP include the following:

- New insights into the structure of scattering amplitudes in quantum field theory and gravity, and associated foundational components of field theory and conformal field theory.
- Developments in the basic understanding of thermal systems, the relativistic hydrodynamic regime, and its applications e.g. to the quark-gluon plasma.
- New understanding of the phase structure and dynamics of strongly-coupled gauge theories.
- Developments in understanding holography, and the connections of black holes and spacetime structure to quantum information theory.
- New insight into the quantum features of black holes, entropy, and low dimensional models of quantum gravity.
- Varied developments in understanding quantum field theory in the very early universe, in de Sitter space times, and the implications for gravitational wave signatures.

Canada has high-profile theory centres, including the Perimeter Institute, but the formal theory community is diverse, and widely distributed across Canada. Researchers actively collaborate in small teams that are often international with members in multiple countries.

SCIENCE DRIVER —

Hadron Properties and Phases

THE NATURE OF quarks and gluons, the fundamental constituents of hadrons, is one of the major unsolved problems of modern physics. Strong interactions between quarks and gluons at very high energies (short distance scales) are described within the Standard Model by the theory of Quantum Chromodynamics (QCD), but a full understanding of the strong force at long distances, where quark confinement dominates, is one of the major unsolved problems of subatomic physics.

To gain insight into the strongly interacting, non-perturbative regime of QCD, where quark (colour) confinement dominates, a number of different approaches are being followed. One strategy is to measure hadron properties such as mass, spin and polarizability, in electron scattering and photoproduction experiments. Another is to search for hybrid mesons predicted to exist by lattice QCD calculations as a means to understand how the quark and gluonic degrees of freedom that are present in the fundamental QCD Lagrangian manifest themselves in the spectrum of hadrons. Evidence for new types of hadrons, including tetraquark and pentaquark state, are exciting discoveries which strongly motivate further study. Measurements of the electromagnetic form factors of mesons, such as the charged pion and kaon, will elucidate the role of confinement and chiral symmetry breaking in fixing the hadron's size and mass as well as the transition from the perturbative-QCD to strongly-coupled domains (short to long distances). Exotic matter can also be created by colliding nuclei at relativistic energies, creating conditions similar to those that existed shortly after the Big Bang, which informs the construction of the phase diagram of nuclear matter.

Canadian Contributions and Achievements

Canadians are at the forefront of the quest to understand the properties of hadrons, on both the experimental and theoretical fronts. Canadian achievements in the past five years include the following.

- The Canadian theoretical community leverages a range of calculational approaches, including Lattice QCD, Light Front Holographic QCD and Chiral Pertubation Theory to advance the field and to support the Canadian experimental efforts. For example, recent achievements include the first direct lattice QCD calculation predicting the existence of tetraquarks with valence content $ud\bar{b}\bar{b}$, and calculations of the Standard Model predictions for the differential branching ratio of the rare decay $B_s \to \phi\mu^+\mu^-$.

- The GlueX project currently taking place at Jefferson Lab aims to measure the properties of hybrid mesons produced through photo-production. Canadians have maintained responsibility for the gain calibrations of the silicon PMTs for the Barrel calorimeter which was designed and built in Canada. The Canadian team also led the measurement of the photon-beam asymmetry for η and η' mesons, concluding that this photoproduction process is dominated by natural parity exchange with little dependence on momentum transfer.

- The pion form factor program at Jefferson Lab has been led by Canadians, garnering over 1,000 citations for their work collecting and analyzing the data from various experiments.

- Canadians have conducted a program of measurements to extract the spin polarizabilities of the proton at the Mainz Mictrotrom (MAMI) in Germany. Such polarizabilities are fundamental observables of hadron structure, and are amenable to calculation with various QCD-inspired models and effective theories. Several measurements have been published and shown to be in agreement with several different types of predictions obtained using different theoretical approaches.

- Canadians continue to play a pivotal role in the investigation of ultra-relativistic heavy ion collisions in general, and the properties of the quark-gluon plasma in particular, through the calculations of relevant experimental observables using hydrodynamics techniques and the development of this formalism. Canadian involvement in these efforts has spurred the development of the requisite detector concepts at past and future heavy ion colliders, as well as advancing our knowledge of hadron structure.

SCIENCE DRIVER —

Nuclear Structure

ATOMIC NUCLEI, THE core of all visible matter, constitute unique many body systems of strongly interacting fermions. The properties and structure of nuclei are of paramount importance to many aspects of physics, at scales from 10^{-15}m (the proton radius) to 10^{4}m (neutron star radius), and to the evolutionary history of the universe. Many of the phenomena encountered in nuclei also share common basic physics ingredients with other mesoscopic systems, thus making nuclear structure research relevant to other areas of contemporary science, for example in condensed matter and atomic physics.

A wide variety of nuclei exist in the universe, but traditional nuclear models are based on the properties of just those that exist on Earth or can be created artificially with relatively long half-lives. The rare isotopes, with nuclei towards the limit of nuclear binding, provide a new window into nuclear structure. Their observed properties are showing unexpected deviations from current models, thereby challenging our fundamental understanding of nature's principles in building these many-body quantum systems.

Current research in low-energy nuclear physics addresses the existence of atomic nuclei, their limits, and their underlying structure. It also aims to describe interactions between nuclei and dynamical processes such as fission. The ultimate goal is to develop a predictive understanding of nuclei and their interactions grounded in fundamental QCD and electroweak theory. The current challenges of nuclear structure are captured by the following overarching questions. How does the structure of nuclei emerge from nuclear forces? What new features and phenomena emerge with large neutron-proton asymmetry in rare isotopes? A third question, concerning the role of rare isotopes in shaping the visible matter in the universe, leads to the final science driver discussed in the next subsection.

Answers to these questions will follow from a broader and deeper understanding of atomic nuclei, both experimentally and theoretically. The last decades have seen progress in our understanding of the strong nuclear force. However, studies of exotic nuclei, enabled by the developments of rare isotope beams, are changing the conventional knowledge of how protons and neutrons are organized, especially with a large neutron-to-proton asymmetry at the limits of nuclear binding. For example, new forms of nuclei, nuclear halos and neutron skin appear. The well-established shell gaps near stability are also eroded by the spin-isospin effects of the two-nucleon ($2N$) and three-nucleon ($3N$) forces and new magic numbers appear far from stability.

Exploration of rare isotopes towards the extreme limits of N and Z binding will provide the insights needed for a comprehensive understanding of nuclei. This exploration is revealing novel quantum many-body features and leading us toward the true global understanding of complex quantum systems and of the mechanisms responsible for the emergent features found in atomic nuclei. Furthermore, it will open new avenues to cross-discipline contributions in basic sciences and societal applications.

Canadian Contributions and Achievements

Canada is a world-leader in the theoretical descriptions of atomic nuclei from first principles. The ultimate goal of these efforts is to develop a predictive ab-initio theory of nuclear structure and nuclear reactions, to understand nuclei studied at rare isotope facilities. A strong collaboration between Canadian experimentalists and theorists exists and has led to feedback on the quality of inter-nucleon interactions used as input to these calculations, improving the knowledge of the $2N$ and $3N$ forces. The following list highlights recent Canadian achievements in the past five years.

- Canadians have helped reveal the imprints of the nuclear force from a study of proton elastic scattering on ^{10}C. The Canadian led experiment, carried out with the IRIS facility at the TRIUMF-ISAC laboratory, measured the shape and magnitude of the differential cross section. Ab-initio nuclear reaction calculations performed by a collaboration led by the TRIUMF theory group, showed that those observables are strongly sensitive to the nuclear force prescription. Comparison with the data suggests that the N^2LO_{sat} chiral effective interaction does a better job, compared to the other forces, but is still not an adequate description of the nuclear force.

- The observed β-decay rates in nuclei, found to be systematically smaller than for free neutrons, implies apparent quenching of the fundamental coupling constant. An international theory collaboration, with key contributors from the TRIUMF nuclear theory group, has recently solved this 50-year-old puzzle from first-principles. Their work showed that this quenching arises to a large extent from the coupling of the weak force to two nucleons as well as from strong correlations in the nucleus. Combining effective field theories of the strong and weak forces with powerful quantum many-body techniques, the group carried out *ab-initio* calculations of β-decays from light- and medium-mass nuclei up to ^{100}Sn that are consistent with experimental data. These results also have implications for heavy element synthesis in neutron star mergers and predictions for the neutrino-less double-β-decay.

- Canadians have also made important contributions to the measurement and understanding of Halo nuclei. For example, recent studies with Canadian leadership with the Radioactive Ion Beam Factory (RIBF) at the RIKEN Nishina Centre in Japan have unveiled a two-neutron halo in ^{29}F. It is the heaviest and the first Borromean halo observed in the proton sd-shell to date. While the results are explained by state-of-the-art shell model calculations with effective interactions, ab-initio predictions are challenged in explaining the halo in ^{29}F, pointing once more to our limited knowledge of the nuclear force from first principles.

- Canadians contributed to high-precision mass measurements of $^{50-55}Sc$ isotopes at LEBIT and the TITAN facilities at TRIUMF. This work added important information to the understanding of emerging closed-shell phenomena at N=32 and N=34 above the Z=20 magic number. Specifically, the new data enabled a complete and precise characterization of the trends in ground state binding energies along the N=32 isotone, confirming that the empirical neutron shell gap energies peak at the doubly magic ^{52}Ca. Furthermore, the results suggest that closed-shell behavior only appears in the mass surface for $N \leq 20$.

- Canadians led the recent study of the structure of ^{80}Ge using the GRIFFIN spectrometer at TRIUMF-ISAC. The new experimental evidence combined with shell model predictions clearly indicated that low-energy shape coexistence is not present in ^{80}Ge, in contrast to previously reported results.

SCIENCE DRIVER —

Cosmic Formation of Nuclei

HUMANITY HAS LONG sought to understand the origin of visible matter and the abundance of the known stable and long-lived nuclei. While it has been firmly established that the synthesis of elements in the universe occurs through a variety of nuclear processes, from quiescent stellar burning to dynamic conditions involving the remnants of stellar explosions and compact object mergers, only half of the total number of nuclei that are expected to exist between the neutron- and proton-dripline have been discovered, about 3,450 nuclei. Much work remains to precisely understand the different nucleosynthesis processes at play.

Understanding nucleosynthesis is accomplished by a combination of astrophysical observations and simulations, nuclear physics data, and the input of nuclear theory predictions. Specifically, from a nuclear physics point of view, the study of astrophysical reactions of interest and knowledge of properties of the nuclei involved requires stopped and accelerated radioactive ion beams such as those produced by the ISAC and ARIEL facility at TRIUMF. Nuclear physics measurements can also help elucidate the physics of neutron stars, the smallest and densest objects in the universe, and supernovae explosions, in particular through precise measurements of the neutron skin thickness in neutron-rich nuclei that help constrain the equation of state of neutron-rich nuclear matter.

This field is also highly synergistic with multi-messenger astronomy, as best evidenced in the remarkable simultaneous observations of the binary neutron star merger GW170817 at multiple electromagnetic wavelengths, triggered by gravitational wave interferometry.

Canadian Contributions and Achievements

Research efforts in the Canadian nuclear physics community cover all the processes of nucleosynthesis and associated astrophysical phenomena. The ISAC and ARIEL facilities at TRIUMF in Canada bring immense scope for such studies, and Canadians are leading many of these projects. Canadians are also involved in selected projects at offshore facilities with complementary technology. Some research highlights since the last LRP are summarized below:

- Direct measurement of the proton capture reactions at astrophysical energies are possible using the recoil spectrometers DRAGON and EMMA at TRIUMF. Using this infrastructure, Canadians have recently achieved the measurement of the ^{38}K(p,γ)^{39}Ca reaction, greatly reducing the uncertainties in the knowledge of the mechanism involved in the Ar, K and Ca synthesis. Canadians have also exploited the joint capabilities of the

EMMA and TIGRESS detectors at TRIUMF to make the first measurement of the ^{83}Rb(p,γ)^{84}Sr reaction, an important measurement in the *p*-process for constraining the reverse reaction.

- Canadians have contributed to several leading studies of nuclear properties relevant to the understanding of nucleosynthesis processes. For example, Canadians performed precise mass measurements of neutron-rich Ga and In isotopes for *r*-process nucleosynthesis using the TITAN Penning trap and also contributed to the precise measurement of the half-life of ^{130}Cd with the GRIFFIN spectrometer at TRIUMF, resolving the discrepancies between previous measurements for this crucial *r*-process nucleus. Canadians have also been engaged in the BRIKEN project at RIBF in Japan measuring half-lives and neutron-branching ratios for the most exotic neutron-rich nuclei over a wide mass range, and have led the development of a reference database on beta-delayed neutron emitters at the International Atomic Energy Agency (IAEA).

- Canadian researchers have been developing programs to indirectly measure the rate of neutron capture in the synthesis of heavy elements using the infrastructure at TRIUMF, Michigan State University and Argonne National Lab.

- Canadian researchers have been leading ongoing efforts to measure the neutron skin thickness in ^{48}Ca via parity violating electron scattering using the CREX experiment.

- Canadians have continued to maintain a world-leading position in predicting nuclear structure properties that are necessary for nuclear astrophysics. For example, Canadians have achieved impressive level of precision in calculating direct capture rates of the ^{8}Li(n,γ)^{9}Li reaction using *ab initio* reaction theory. Canadians have also been pursuing astrophysical simulations of binary mergers.

Impact and Synergies with Other Fields

THE OVERARCHING GOAL of subatomic physics, to push the frontier of our knowledge of what the universe is made of, and the associated development of specialized research tools, naturally leads to strong links with many other research fields.

Unique opportunities and synergies exist at the boundary between subatomic physics research and other fields, along both scientific and technological fronts. From the scientific point of view, findings in the fields of astrophysics and cosmology provide complementary information in addressing several of the subatomic physics science drivers, and in turn the advancement of knowledge in subatomic physics has a direct impact on models of cosmology and astrophysics phenomena. For example, the rapidly developing multi-messenger approach to study astrophysical objects lies squarely at the boundary between the fields of subatomic physics and astrophysics. From a technological standpoint, techniques and instruments developed for subatomic physics research have been, and continue to be, adapted for use in a wide range of other fields, paving the way to innovative and ground-breaking work. These fields include biology, data science, electrical engineering, material science, medical imaging and public health. Specific examples of these synergies include particle detection techniques used in medical imaging, accelerator mass spectrometry employed in biomedical research and in archaeology for radiocarbon dating, applied nuclear imaging of plants and soil and muon tomography used in several areas such as geology, security and environmental protection. In turn, developments in quantum sensing and techniques in atomic, molecular and optical physics offer novel, and possibly groundbreaking, opportunities to address science drivers in subatomic physics. Developments in accelerator technology to support subatomic physics also have applications to accelerators supporting material science, medical diagnosis and treatment as well as industrial applications such as security, environment, and food storage.

In summary, there exists valuable scientific opportunities in cross-disciplinary collaboration at the boundaries between different fields of research, and subatomic physics research is uniquely positioned to contribute to and benefit from initiatives in regions of overlap with other fields (see FIGURE 2).

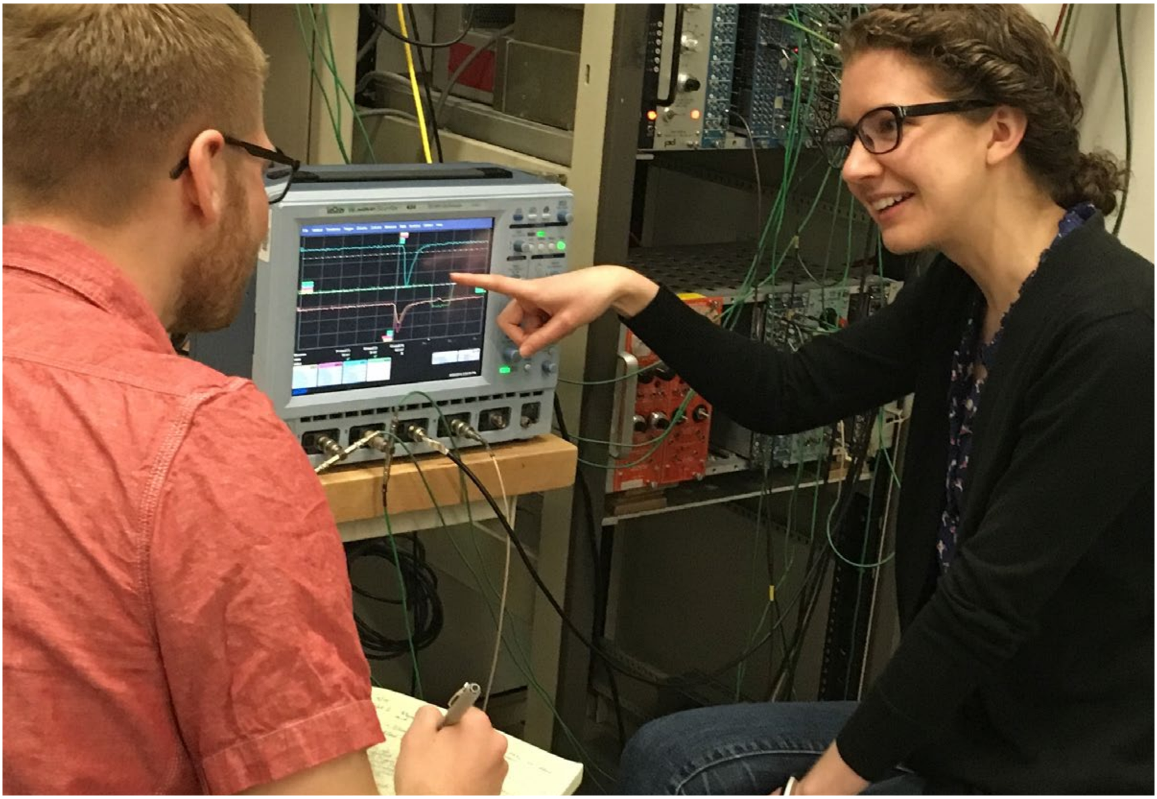
FIGURE 2. Schematic representation of the eight science drivers for the field of subatomic physics research and examples of synergies with other research fields.

The SuperCDMS collaboration is searching for dark matter particles with masses smaller than ten times the mass of the proton. Detecting these particles would revolutionize our understanding of the subatomic world and open a window into a completely unknown set of new particles.

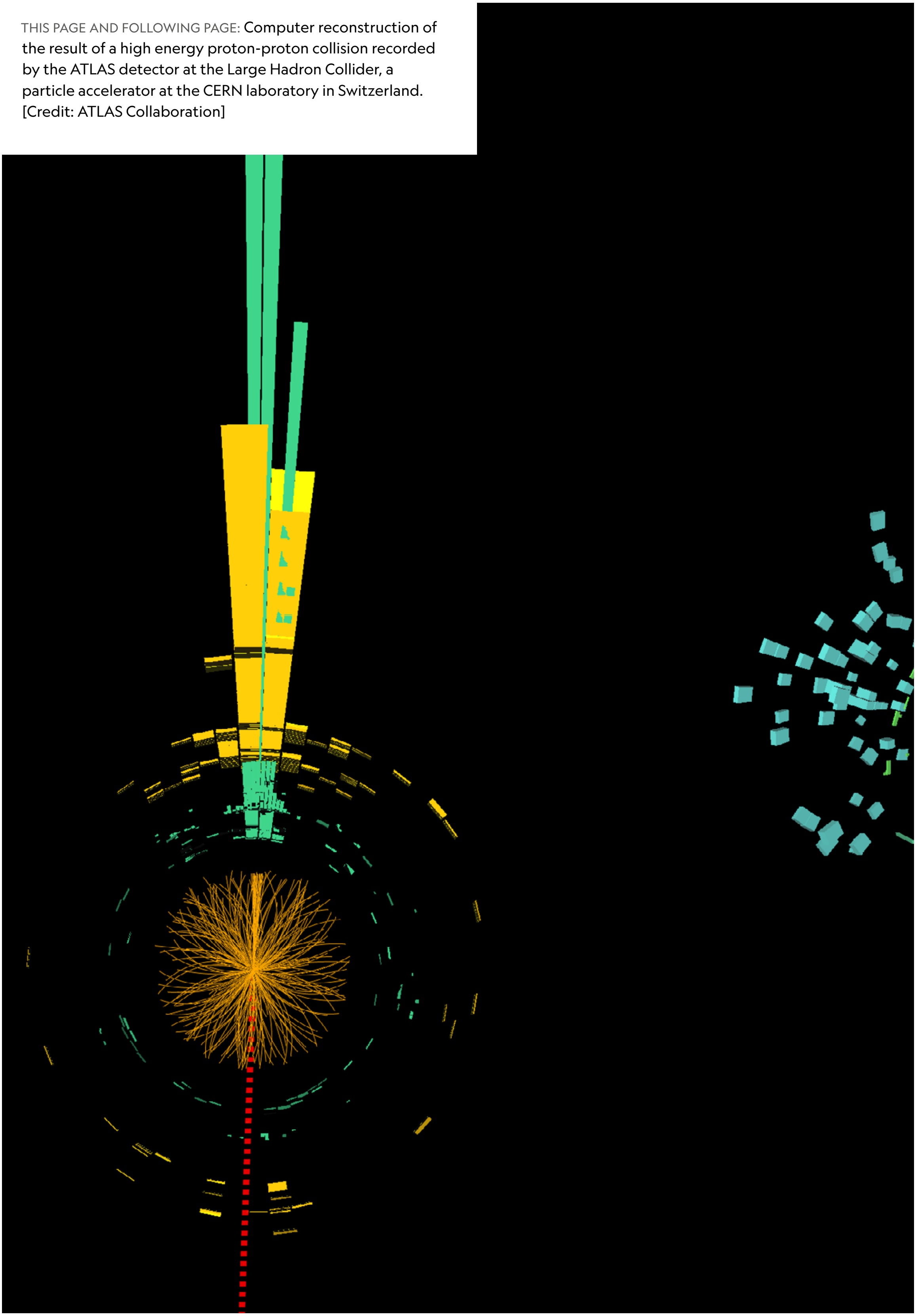
THIS PAGE: Undergraduate student helping to prepare a new SuperCDMS detector for a first test under low-background conditions in the Cryogenic Underground TEst facility (CUTE) at SNOLAB. [Credit: SNOLAB]

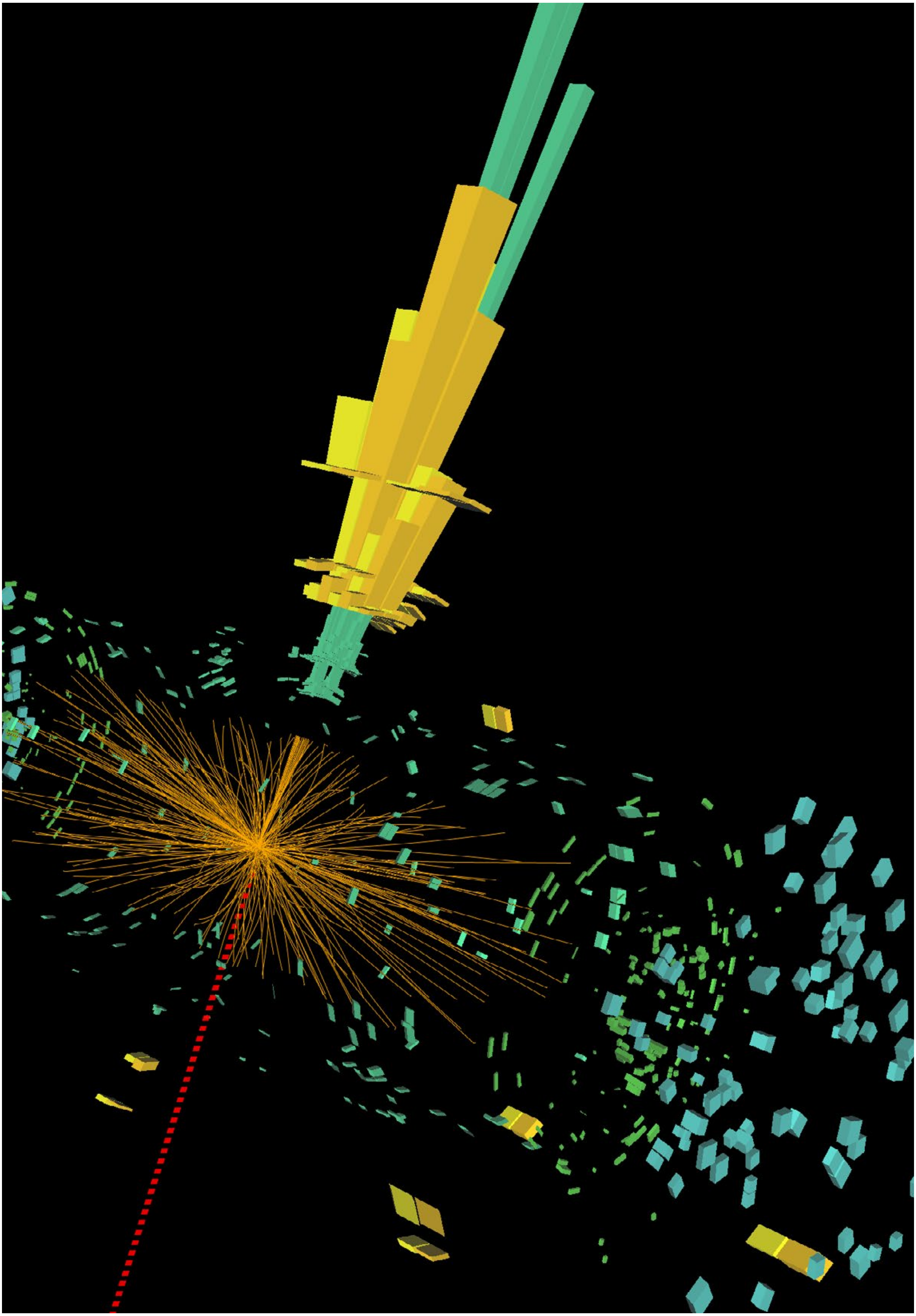
FOLLOWING PAGE, TOP: A graduate and undergraduate student discussing technical aspects of the SuperCDMS experiment. [Credit: SLAC]

FOLLOWING PAGE, BOTTOM: The SuperCDMS Engineering Tower to be installed at SNOLAB. [Credit: SLAC]



THIS PAGE AND FOLLOWING PAGE: Computer reconstruction of the result of a high energy proton-proton collision recorded by the ATLAS detector at the Large Hadron Collider, a particle accelerator at the CERN laboratory in Switzerland. [Credit: ATLAS Collaboration]





SECTION 2 –
Canadian Subatomic Physics Research Plan

WITH AN established track record; ongoing and newly developing international partnerships; valuable local research facilities such as TRIUMF, SNOLAB and the Perimeter Institute; and significant recent support for the development of experimental infrastructure, the Canadian community is poised to capitalize on a number of science opportunities over the coming five years, and the decade beyond. This section outlines the emerging science opportunities and the enabling technologies that will support progress. The research program is then presented in the form of a multi-dimensional portfolio of projects that will help the Canadian community maximize its scientific impact, training opportunities, and benefits to society. The existing portfolio, and emerging opportunities lead to a series of Science Recommendations.

Science Opportunities for Canada

UNIQUE FEATURES OF the Canadian subatomic physics research ecosystem position the community well to seize emerging scientific opportunities, with the goal of maximizing scientific impact, training opportunities and benefits to society. In particular, Canada has significant research infrastructure in TRIUMF, SNOLAB, and the Perimeter Institute. In addition, there are active community organizations and flexible funding structures to support new scientific initiatives. Canada also has an excellent standing as a trusted international partner, and the community has the capacity to train additional highly qualified personnel (HQP).

Several scientific opportunities exist in the coming years, and these are highlighted for each of the science drivers in the following sections.

SCIENCE DRIVER — Higgs, physics at the electroweak scale, and beyond

In the coming decade, there will be unique opportunities to thoroughly explore the Higgs sector, study the physics of electroweak symmetry breaking, and search for new physics at the energy frontier, with significant prospects for a wide range of exciting new results. Dedicated searches for unconventional physics signatures will also offer significant discovery potential. There will be several opportunities to indirectly explore new regions of multi-TeV physics through measurements of known and rare physics processes at an unprecedented level of precision, providing complementary possibilities for observing hints of new physics. It is also likely that by the end of the decade, the situation with respect to persisting anomalies in the B-physics sector pointing to possible lepton flavour violation will be clarified.

Building on its expertise and past investments, Canada is well-positioned to pursue further scientific opportunities through its participation and leadership, for example, in the broad physics programs of ATLAS and Belle II, dedicated searches for new physics at MATHUSLA and MoEDAL, and precision programs such as those of MOLLER and NA62. There is also an active Canadian theory community engaged in interpreting new data and pointing to potential signatures of new physics. Finally, there is the opportunity to advance detector and accelerator R&D synergistically with contributions to the HL-LHC, the development of Chiral Belle, the International Linear Collider and the Future Circular Collider projects.

SCIENCE DRIVER — Fundamental Symmetries and Observed Asymmetries

Exploration of the fundamental symmetries in subatomic physics and their violation will continue to be at the forefront of searches for new physics phenomena and principles, providing powerful and complementary sensitivities. Opportunities exist for probing symmetries to a new level of precision by exploiting a variety of different techniques.

Within the landscape of possibilities, the combined Canadian expertise in atomic, nuclear, particle physics and accelerator research offers unique opportunities for Canada to play a scientifically leading role world-wide. TRIUMF can become a global centre for tests of *CP* and *T* violation via EDM searches, with the start of operations for the Canadian-led TUCAN project, the FrEDM experiment, and the development of the RAMS facility using radium monofluoride and francium silver molecules. New tests of parity violation can be achieved with FrPNC, studies of beta decays with ISAC and TRINAT at TRIUMF, and the launch of Nab operations at ORNL. Canadians are also well-positioned to play a significant role in future tests of the electroweak symmetry structure and the running of the Weinberg angle with the development of MOLLER, along with Belle II and the possible Chiral Belle upgrade. Spectroscopic tests of anti-hydrogen with significantly improved precision will be feasible with ALPHA-3 and ALPHA-g, and the deployment of Canadian-led HAICU. Tests of lepton flavour universality will continue with NA62 at CERN, and the potential development of PIONEER. Tests of neutrino properties and *CP* violation will continue with long-baseline neutrino experiments such as T2K and will move to the next generation of precision with Hyper-K and DUNE operations. Tests of lepton number violation via neutrinoless double beta decay can be further explored with next generation experiments such as nEXO, LEGEND or other detectors complementing the existing SNO+ program at SNOLAB.

SCIENCE DRIVER — Neutrino Properties

The coming decade should be another exciting one for neutrino physics. At its conclusion, it is likely that the mass hierarchy will be determined, and the search for CP violation will be well underway, potentially yielding conclusive results. At the same time, searches for $0\nu\beta\beta$ will have continued to push forward, and will likely have achieved sensitivity to span the inverted hierarchy parameter space. Measurements of astrophysical neutrinos will have continued to inform us about the highest energy processes in the cosmos, and neutrinos will have further illuminated our understanding of the workings of the Sun and the interior of the Earth. Research in neutrino physics continues to move forward with vigour, and new breakthrough discoveries are a distinct possibility.

Canada is well-positioned to play a leading role in all of these scientific achievements, with the development of Hyper-K and DUNE, the evolution of IceCube and potential development of P-ONE, and the primacy of SNOLAB as the preferred location for tonne-scale experiments such as nEXO and LEGEND.

SCIENCE DRIVER — Dark Matter and Potential Dark Sectors

Significant breakthroughs in our understanding of the nature of dark matter are possibly within reach in the next decade. Experiments designed to directly detect the presence of dark matter in our galactic halo are likely to achieve significant increases in sensitivity through the continuing development of experimental techniques. As experimental sensitivity approaches the important background from solar and atmospheric neutrinos (the so-called "neutrino floor"), possible new directions include the development of experiments capable of exploring diverse mass scales, dark matter electron scattering, and directional capability in the reconstruction of dark matter interactions. In the coming decade, several accelerator-based projects aiming to produce dark matter and particles related to a possible dark sector should also have acquired significant data allowing further direct tests of this paradigm. The search for dark matter through observation of its annihilation signatures will be pursued using a variety of observatories of increasing sensitivity. The Canadian astroparticle theory community is also well-positioned to play a synergistic role in this effort.

Canada has a bright future in the search for dark matter and is in an excellent position to seize these scientific opportunities. The Cryogenic Underground Test Experiment (CUTE) infrastructure at SNOLAB will enable early exploitation of the SuperCDMS crystals for physics results. By the end of the decade, the SuperCDMS experiment at SNOLAB, will have explored a large swath of parameter space for low mass WIMPs and approach sensitivity to the solar and atmospheric neutrino background. The DEAP collaboration has joined the Global Argon Dark Matter Collaboration with the goal of running DarkSide-20k at the Gran Sasso Underground Laboratory (LNGS) in Italy and then a multi-hundred tonne detector ARGO with SNOLAB being the preferred location. The PICO experiment is expected to continue to improve its leading sensitivity in the spin-dependent WIMP sector, while the new

SBC experiment will adapt this exciting new scintillating bubble-chamber technology to the search for low mass WIMPs. The NEWS-G experiment is also poised to make interesting contributions to the low mass regime and will explore directional sensitivity using a novel composite central anode in its detector. High-precision accelerator-based dark sector searches will be carried out at ATLAS, Belle II, NA62, MoEDAL and MOLLER. The DarkLight experiment is also preparing a technical design report for use of the intense ARIEL electron beam on a thin target at TRIUMF to explore dark sectors. Canadians will also take part in the commissioning and operation of a demonstrator for the future MATHUSLA project. Indirect searches for dark matter annihilation will continue at IceCube.

SCIENCE DRIVER — New Physical Principles and Structures

Canadian theorists pursuing a deeper understanding of the foundations of subatomic physics have established global stature across a range of research sub-fields. This presents opportunities for progress in several topical areas. Canadian theorists are pursuing basic questions about the underlying structure of quantum field theory, including improved methods for calculating scattering amplitudes, the geometric structures that underpin them, and the consistency constraints on allowed quantum field theories in the strong coupling regime. The role of quantum information theory in quantum field theories is another growing area of theoretical activity across Canada; through the AdS/CFT correspondence, this work is driving an understanding of the black hole information paradox, Hawking radiation, and quantum gravity more generally. Holography (the AdS/CFT correspondence and its extensions) also continues to present opportunities to advance our understanding of strongly coupled gauge theories, with ongoing progress modeling nuclear physics such as the quark-gluon plasma, and hydrodynamics. Further research opportunities within string theory target an explanation for various features of the Standard Model, as well as properties of the vacuum, such as a cosmological constant or dark energy. This also connects to further avenues for progress, as theoretical developments in quantum field theory may provide new ideas about the very early history of the universe and its initial conditions. Cosmological observations promise in turn to provide more information about the high-energy nature of subatomic physics, including the properties of dark matter. The universality of formal theoretical tools used in subatomic physics also presents opportunities for connections to other areas, including astrophysics, condensed matter physics, and quantum computing.

Formal theoretical efforts are primarily motivated by the goal of identifying underlying structures that can systematize and extend our theoretical understanding of fundamental physics. However, over the long term, formal research will continue to feed back to more phenomenological areas of subatomic physics to inform our understanding of many of the other science drivers, as it has in the past. Canadian theorists are strongly positioned to advance formal theory on a number of fronts, providing new directions for phenomenological and experimental subatomic research over the long term.

SCIENCE DRIVER — Hadron Properties and Phases

In the coming decade, new experimental capabilities and advances on a range of theoretical fronts will help to shed light on nucleon structure and hadron properties.

Upgraded detectors for GlueX at JLab and at MAMI will extend the reach in precision and available nuclear targets. The proposed JLab Eta Factory (JEF) involves a significant upgrade to the GlueX base instrumentation, enhancing the energy and position resolution, and allowing for unprecedented precision in exotic hybrid meson searches. The Solenoidal Large Intensity Detector (SoLID) at JLab will study Generalized Parton Distributions, which can provide a tomographic 3D picture of the nucleon. Neutron spin polarizability measurements will be possible with a combination of measurements on He and He at MAMI, with the development of an active, high-pressure helium target.

Looking ahead, the future Electron-Ion Collider (EIC) is the only North American collider to be constructed for the foreseeable future and it is on Canada's doorstep. The new opportunities at the EIC will make it possible to achieve a transformational understanding of the dynamical system of quarks and gluons. There is significant synergy between the EIC and 12 GeV JLab program, with a rich and diverse set of experiments capable of precisely studying QCD, from the nature of the finite temperature many-body problem, to mapping the transition from hadronic to partonic degrees of freedom. Canadian researchers are involved in all these projects, from forefront theoretical activities to the development of enabling technologies for the EIC like crab cavities, and are poised to make significant discoveries about hadron structure.

SCIENCE DRIVER — Nuclear Structure

Developing a predictive understanding of nuclei and their interactions requires a wide variety of complementary experiments and theoretical tools. The coming decade will see the start of operations of new-generation infrastructure that will enable a systematic study of nuclear properties and patterns, potentially opening up a window to new and unexpected phenomena.

In Canada, the ARIEL facility and the CANREB project at TRIUMF will come online, promising a tripling of beam-time and extending the physics capability and reach for nuclear structure research. Canadian scientists will also continue to play a decisive role globally by contributing to the development of unique instruments and leading physics programs at RIBF(Japan), FAIR (Germany) and FRIB (USA).

The development of new ab initio theory, for both nuclear structure and interactions, is also Integral to this program. The synergy between experiment and theory, in terms of designing the most sensitive experiments and the feedback on the theoretical framework, will be crucial to shape a path towards the overarching goal of the field: a predictive standard model of nuclei.

SCIENCE DRIVER — Cosmic Formation of Nuclei

The next decade will offer new scientific opportunities in studying heavy element synthesis due to the significant increase in the infrastructure for radioactive beams worldwide, combined with multi-messenger observations of neutron star mergers. For example, it will be possible to directly study the key reactions and short-lived nuclei required to understand the reaction pathways of explosive astrophysical events.

Canada is uniquely positioned to assume a leading role in these investigations with the start of operations for the ARIEL and CANREB facilities at TRIUMF. To fully exploit TRIUMF's future beam capacity, various extensions to and upgrades of existing experimental capabilities are planned. For examples, a $LaBr_3$ array is being planned that aims to achieve a ten fold increase in gamma tagging sensitivity of DRAGON. To enable new directions in reaction cross section measurements, especially with $^{3,4}He$, an active target time projection chamber (EXACT-TPC) is also being planned.

Offshore infrastructure will also offer new scientific opportunities. For example, higher intensities of rare nuclei will extend the reach in studying exotic decays with, for example, highly-charged ions in storage rings or beta-delayed multi-neutron emitters at GSI/FAIR. Measurement of the neutron skin thickness of neutron-rich nuclei, relevant for exploring the equation of state of asymmetric nuclear matter, is also planned at GSI/FAIR and at FRIB.

Future developments in ab initio theory promise to extend the reach to high-mass nuclei utilizing exascale computing power and the development of quantum computing and algorithmic capabilities. In the modeling of compact object mergers a variety of new developments are planned including molecular dynamics simulations.

In the longer term, the installation at TRIUMF of a low-energy storage ring with a neutron generator is being explored. This infrastructure project could provide a unique capacity for directly measuring the neutron capture cross sections of rare isotopes.

Opportunities Arising from Synergies with Other Fields

In the coming decade, knowledge acquired in other research fields may also help to advance our understanding of the subatomic physics science drivers. Examples include:

- Future developments in astronomy and astrophysics; e.g. potential gravitational wave signatures of early particle cosmology, potential signatures of dark matter in a number of future ground-based and satellite observatories, developments in the simulation of galaxy structure and formation, and multi-messenger observations of compact object mergers that could provide insight into the equation of state of high density matter.

- Next generation experiments measuring the cosmic microwave background will achieve a significant increase in precision in constraining the nature of neutrinos, dark matter, and dark sectors.
- Developments in the technology of quantum sensing and computing, and theoretical aspects of quantum condensed matter are occurring rapidly and are likely to open further opportunities in exploring the subatomic physics science drivers; some examples will be outlined below.

Likewise, there are opportunities for future subatomic physics research outcomes to have an impact on other related research fields:

- An experimental measurement of the absolute neutrino mass scale could have direct implications in cosmology.
- Precise measurements of new nuclear properties and rates will enable better understanding and modeling of processes in stellar astrophysics.
- Developments in accelerator and detector technology are likely to open further opportunities for research in other fields; examples include the development of
    - new medical physics diagnostics and treatment.
    - applications supporting green technologies.
    - space systems designed for deep space exploration.
    - imaging and tomography instruments for material science.

FIGURE 3. Schematic representation of the eight science drivers for the field of subatomic physics research and enabling infrastructure.

Infrastructure and Enabling Technologies

PROGRESS FOR EACH of the science drivers depends on many factors, but a variety of infrastructure and enabling technologies are critical for both experimental and theoretical developments. These are described below along with their application to each of the science drivers.

Specialized Infrastructure

Subatomic physics research is enabled by and critically relies on the development and availability of unique infrastructure, as shown in FIGURE 3.

Particle Accelerators

Particle accelerator infrastructure continues to be a driving force in the development of experimental particle and nuclear physics, and is an enabling infrastructure for almost all the science drivers. The field of accelerator physics is in turn synergistic with subatomic physics itself, driven by many of the science goals, but with many broader applications. Accelerator infrastructure with significant Canadian access and involvement includes: TRIUMF in Canada, LHC at CERN, J-PARC and KEK in Japan, Fermilab, JLab, RHIC and the future EIC in the US, and MAMI in Germany. Necessary developments for this type of infrastructure in support for subatomic physics research include:

- Accelerator R&D, focused on the Superconducting Radio-frequency (SRF) technology.
- Development of high-luminosity beams (neutrinos, electrons, neutrons, kaons, pions, ions, or antimatter) for precision measurements.
- Development of polarized beams of different species.
- Progress in understanding beam physics allowing precision control for operation at higher intensity or efficiency.

Further development of accelerator technology also involves the study of novel acceleration techniques, such as beam acceleration in plasmas.

Rare Isotopes

Studies of nuclear structure, including those relevant for astrophysical processes that formed the elements, are enabled by rare isotope beams. TRIUMF is a world-class facility that provides unique isotope beams at low energy and near Coulomb barrier energies, with a comprehensive set of detectors for analysis. The completion of ARIEL will significantly grow TRIUMF's capacity to deliver isotope beams.

Complementary capabilities exist at the following offshore rare isotopes facilities with relativistic beams: Facility for Rare Isotope Beams (FRIB) in the USA, Facility for Antiproton and Ion Research (FAIR) in Germany, and the RI Beam Factory (RIBF) at RIKEN in Japan.

Some of the important areas in which development of this infrastructure is required include beam targetry, beam transport and detector capabilities.

Low Backgrounds

Measurements of rare processes and those requiring high precision depend critically on low background facilities. This enabling infrastructure is critical for experimental progress in searches for dark matter and neutrino properties, and for high-precision tests of fundamental symmetries. Facilities with significant Canadian access and involvement include: SNOLAB in Canada, Gran Sasso in Italy, and WIPP in the US. Specific developments in this type of infrastructure required to support subatomic physics include:

- Development and production of ultra-clean materials.
- Development of improved material assay techniques.
- Precisely controlled and monitored electromagnetic fields, beam properties and beam dynamics, as well as high and precisely measured beam polarization.
- Specialized high-precision detectors.

Enabling Tools and Emerging Technologies

Developments in the area of instrumentation, data analysis, theory, and computing enable tool-driven revolutions that can open the door to future discoveries. It is therefore important to maintain and further strengthen a research and development environment that stimulates and supports innovation in these areas.

Detector R&D

Detector R&D is key to enabling future discoveries. As such, it is important that the community sustains and promotes a diversified portfolio of both generic R&D and R&D activities with a focus on solving the known technological challenges of the next generation of experiments. Instrumentation development for subatomic physics is both a driver for, and a beneficiary of, progress made in other areas of subatomic physics and other fields of science and industry, and technology innovation often emerges from these synergies. Examples of detector developments include:

- radiation-hard semi-conductor devices for tracking detectors in future collider experiments.
- high-performance and novel photodetectors.
- low threshold nuclear and electron recoil detection technologies, including quantum sensors.

- capability for measuring combined features such as those associated with the development of 4D tracking and 5D imaging.

Digital Research Infrastructure

Subatomic physics research requires access to state-of-the-art digital research infrastructure with high computing capacity, petabyte-scale storage, and high-speed network connectivity between different computing sites and research centres world-wide, in order to manage large shared datasets. In the coming years, such digital research infrastructure will be provided and managed in Canada by CANARIE and the New Digital Research Infrastructure Organization (NDRIO) currently being established. As highlighted in the Tri-Agency Research Data Management Policy, "research data management (RDM) is a necessary part of research excellence", and in this context, it is important to note that the needs of subatomic physics research include not just general storage of data from experiments but also long-term archival (data preservation) storage.

Analysis, Theory, and Computing

Tools for the analysis of ever-more complex data sets, and the development of the theoretical framework to understand the basic laws of subatomic physics need to evolve in concert with experimental techniques. Subatomic physics has driven the development of many analysis technologies, including Monte Carlo simulation for modelling signal and backgrounds, and the use of machine learning algorithms for data analysis. Meanwhile, developments in phenomenological modelling, computational technologies and in our theoretical understanding, point to new connections and synergies. Specific developments include:

- Machine Learning methodologies in triggering, simulation, and data analysis.
- Quantum Computing and quantum algorithms for reconstructing, simulating, and analysing data from large particle physics experiments.
- New amplitude calculation techniques, that have allowed higher-order analysis of Standard Model backgrounds at colliders.
- New theoretical connections and synergies with other fields, e.g. the use of quantum information tools in analyzing the physics of black holes.

Research Portfolio

IN ORDER TO maximize the impact of Canada's subatomic physics program, accounting for all the opportunities outlined above, the following overarching objectives for the subatomic physics research plan have been identified:

- Focus effort on the most relevant research problems.
- Fully exploit Canada's unique facilities, competitive advantages, and past investments.
- Partner in leading international research projects and deliver on commitments.
- Maintain capacity and flexibility to explore and develop new scientific opportunities.
- Fully engage HQP in all aspects of scientific research to maximize training outcomes.

The LRP Committee sees value for the community in formulating the research plan as a portfolio of research projects, where an optimum balance among various dimensions would maximize the likelihood of scientific impact according to the objectives above while minimizing risk. The axes (or dimensions) of the portfolio include the following:

- Canadian scientific specialization vs breadth.
- Experimental project lifecycle (R&D and construction vs operation and science output).
- Guaranteed scientific output vs high-risk/high-reward.
- Project timeline.
- Theory vs experiment.

With an optimal balance across these dimensions, the portfolio provides a community-led vision of the future subatomic physics science priorities and the most efficient means to tackle them. It also conveys both new science opportunities, inter-connections between research sub-fields, and the need for resources on the longer timelines that are now common for large-scale subatomic physics projects.

A schematic representation of the current subatomic physics research portfolio, in relation to the science drivers, is shown in FIGURE 4.

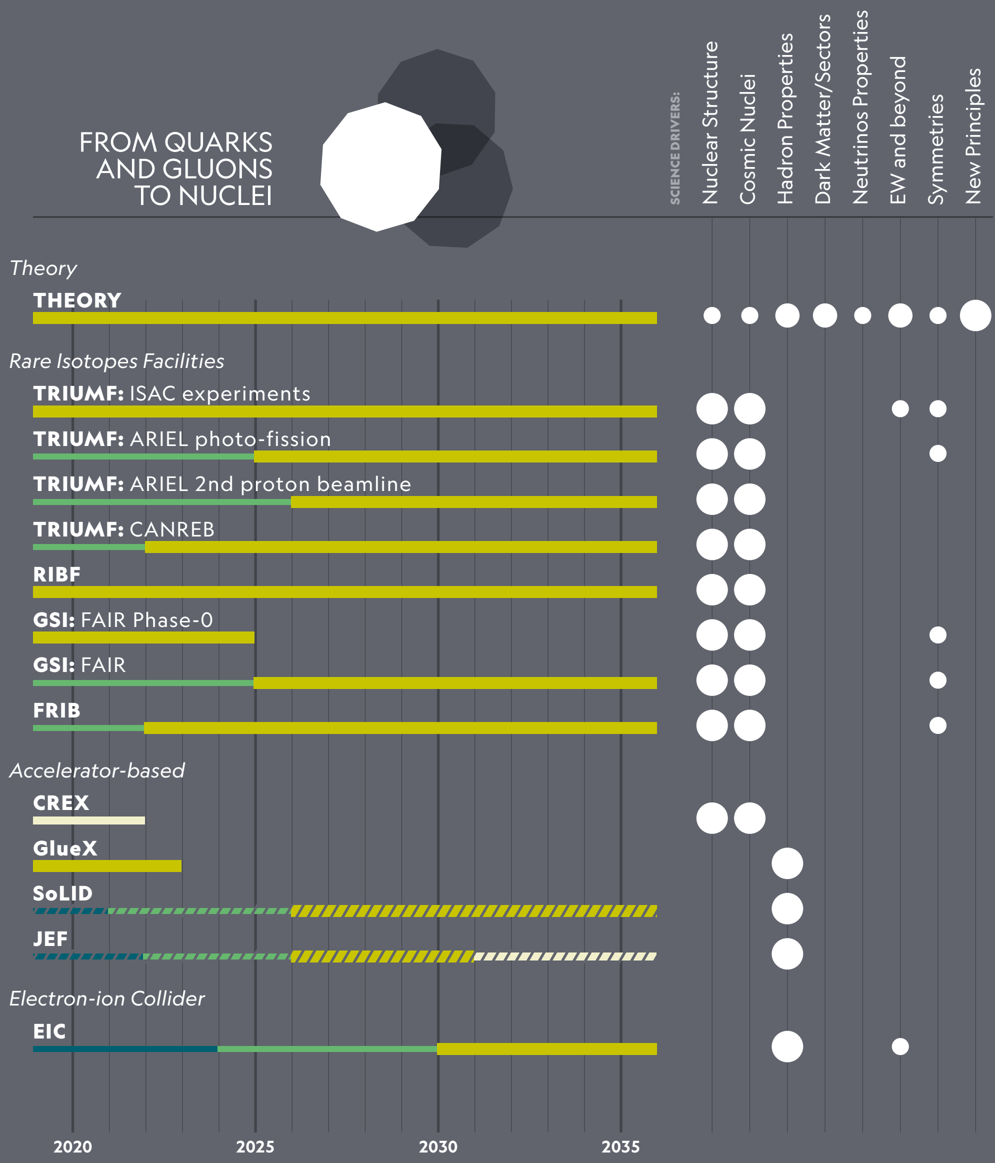
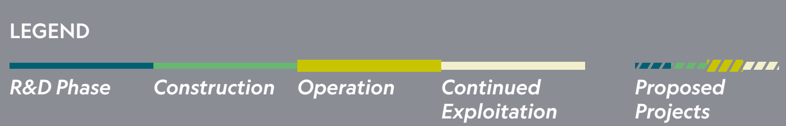
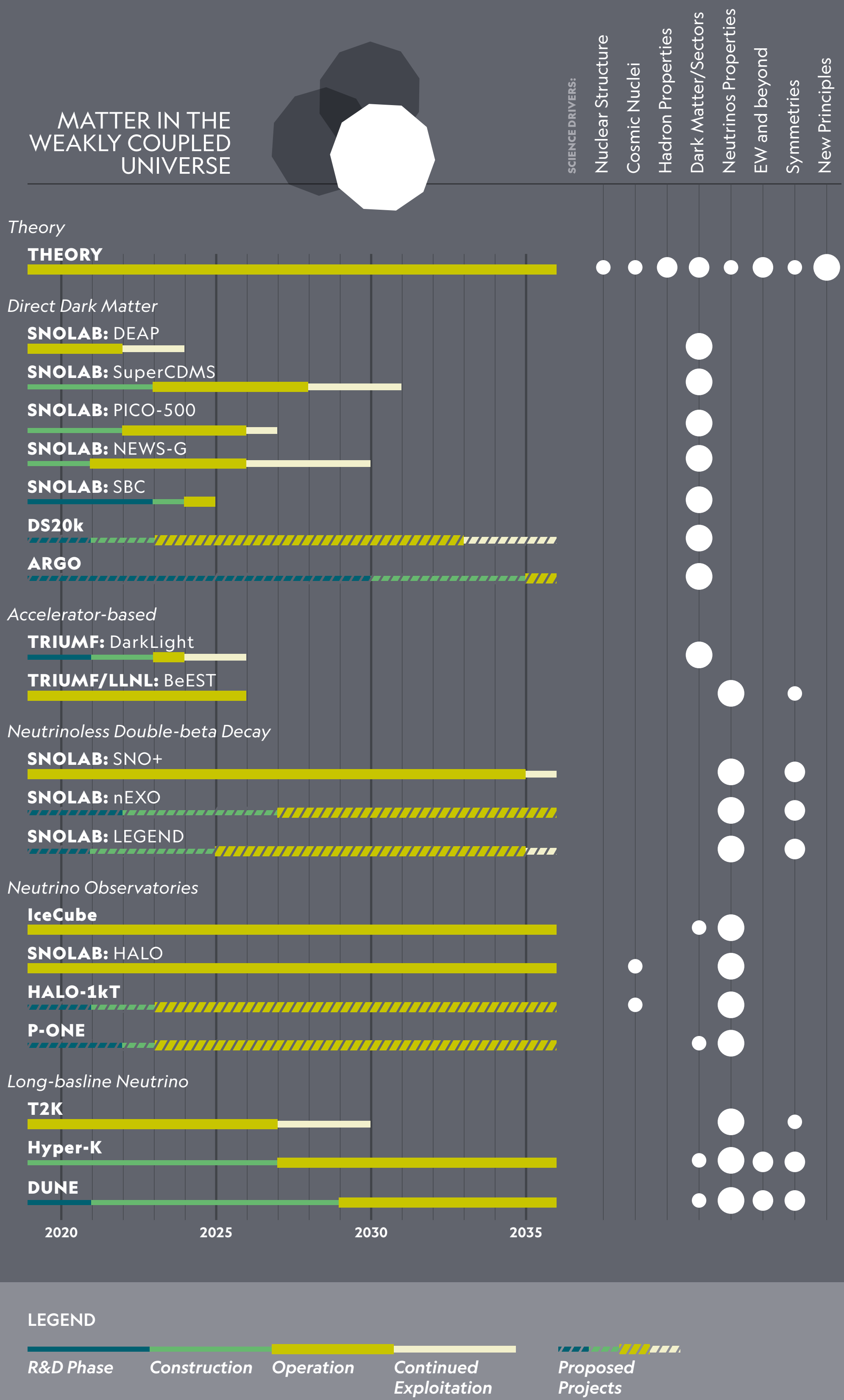
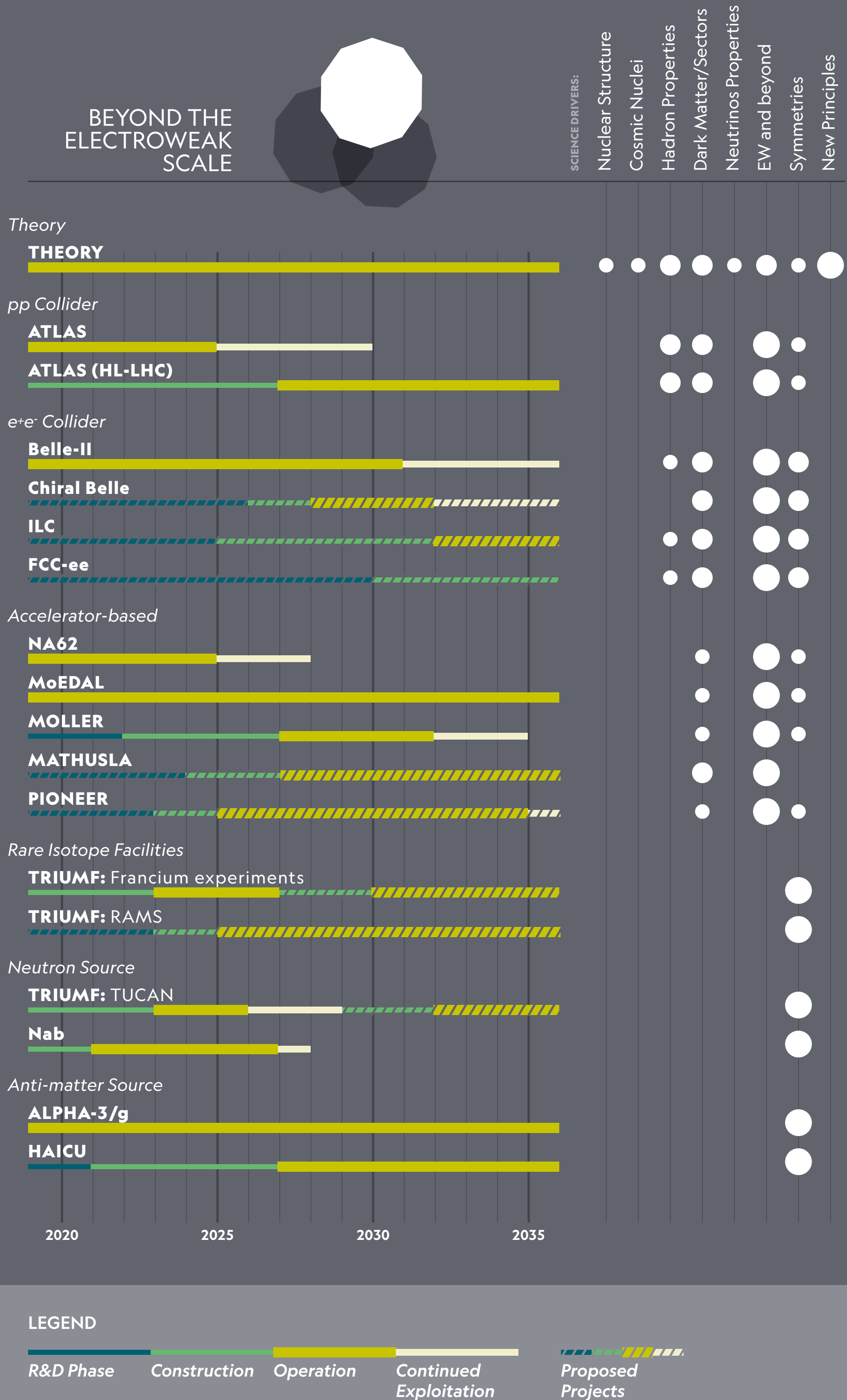


FIGURE 4. A schematic representation of the Canadian subatomic physics research portfolio, with current and approved projects shown in solid colours, and potential future projects with concrete timelines at the time of writing shown in hatched colours.



MATTER IN THE WEAKLY COUPLED UNIVERSE





BEYOND THE ELECTROWEAK SCALE
SCIENCE DRIVERS:
Nuclear Structure
Cosmic Nuclei
Hadron Properties
Dark Matter/Sectors
Neutrinos Properties
EW and beyond
Symmetries
New Principles
Theory
THEORY
pp Collider
ATLAS
ATLAS (HL-LHC)
e+e- Collider
Belle-II
Chiral Belle
ILC
FCC-ee
Accelerator-based
NA62
MoEDAL
MOLLER
MATHUSLA
PIONEER
Rare Isotope Facilities
TRIUMF: Francium experiments
TRIUMF: RAMS
Neutron Source
TRIUMF: TUCAN
Nab
Anti-matter Source
ALPHA-3/g
HAICU
2020
2025
2030
2035
LEGEND
R&D Phase
Construction
Operation
Continued Exploitation
Proposed Projects

Science Recommendations

THE LRP COMMITTEE has developed a number of Science recommendations that build upon the ongoing research activities, as exhibited in the portfolio, and the emerging research opportunities outlined above. These recommendations are described below.

Canada is fortunate to have several world-class subatomic physics research labs and facilities. These include the experimental infrastructure for nuclear physics at TRIUMF, and one of the deepest underground low-background facilities for neutrino and dark matter physics at SNOLAB. In addition, the Perimeter Institute is one of the premier centres in the world for theoretical physics. These centres conduct research, and also act as focal points to stimulate collaboration with the global community. Significant investments have been made over the past decade at TRIUMF, including the development of ARIEL, and at SNOLAB in bringing new experimental space online. It is a high priority that these investments be fully capitalized upon to pursue the new science opportunities that they enable.

SCIENCE RECOMMENDATION
1 — **CANADIAN INFRASTRUCTURE**

We recommend fully capitalizing upon the unique science opportunities provided by the SNOLAB and TRIUMF infrastructure, and by the Perimeter Institute, in pursuit of the science drivers.

Subatomic physics relies critically on both theoretical and experimental developments, as it seeks to understand the basic physical laws. It is vital for the health of the community that theoretical work is pursued along two paths, one that is fully collaborative with nuclear and particle experiment to interpret and understand data and point to new opportunities, and the other to explore new theoretical structures and seek to understand aspects of nature that fall outside the Standard Model, such as the quantum nature of gravity, black holes, and early cosmology. The Canadian theory community has traditionally had significant success in both these directions, and requires support to enable continuing global impact.

SCIENCE RECOMMENDATION
2 — **THEORY PROGRAMS**

Critical mass and research breadth are vital for the theory community in Canada, to maximize the future impact of subatomic physics research. We recommend strong support for theoretical subatomic physics research over the next decade, both to explore new purely theoretical directions and to support the synergistic interaction between subatomic theory and experiment.

The Canadian subatomic physics community has achieved considerable global impact by carefully identifying experimental projects which address the leading scientific questions. The opportunities for the ongoing and future program were outlined above, and the current suite of projects fills out the portfolio represented schematically in FIGURE 4. These considerations lead to the following recommendations for the experimental program.

SCIENCE RECOMMENDATION
3 — **EXPERIMENTAL PROGRAMS**

A broad experimental program is required to address the scientific drivers of subatomic physics research. We recommend pursuit of the following high-priority scientific directions.

- **FROM QUARKS AND GLUONS TO NUCLEI** — *The future program should explore the structure of hadrons and nuclei using rare isotope and accelerator-based facilities. It should include the full exploitation of TRIUMF, offshore electron beam and rare isotope beam (RIB) facilities, and a future electron-ion collider.*

- **MATTER IN THE WEAKLY COUPLED UNIVERSE** — *The future program should incorporate the search for dark matter using complementary direct and indirect techniques, including via multi-ton scale direct detection. The future program should include the further exploration of neutrino properties via neutrinoless double-beta decay experiments, long baseline experiments and neutrino observatories.*

continued on following page →

- **BEYOND THE ELECTROWEAK ENERGY SCALE** — *The future program should study matter and its interactions at increasingly higher energy scales, including the exploitation of a future Higgs factory and energy frontier collider, as well as high-precision indirect techniques.*

This scientific program is currently implemented through Canadian leadership in a set of flagship projects identified based on their potential scientific payoff, Canadian core expertise, the level of community engagement, opportunities for the scientific and technological training of the next generation, and Canadian investments to date:

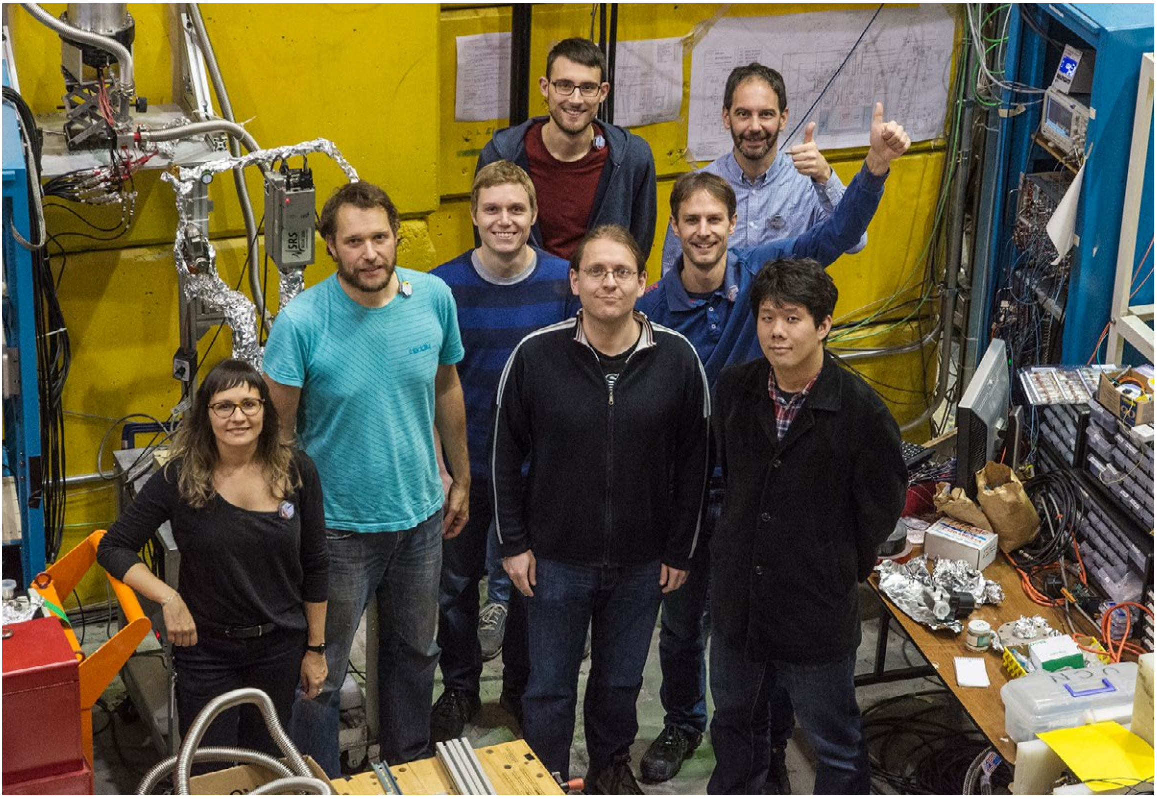
	Flagship projects with broad physics outcomes	***Flagship projects with strategic physics outcomes***
FROM QUARKS AND GLUONS TO NUCLEI	TRIUMF ARIEL-ISAC experiments, EIC	JLab 12 GeV program, Offshore RIB experiments
MATTER IN THE WEAKLY COUPLED UNIVERSE	T2K/HK, IceCube, SNO+	DEAP, PICO-500, SuperCDMS
BEYOND THE ELECTROWEAK ENERGY SCALE	ATLAS(LHC/HL-LHC), Belle II	ALPHA/HAICU, MOLLER, TUCAN

We recommend the support of these projects and also those initiatives within the scientific program, with the potential for high impact, that are under development or may be developed in the coming years. Potential future projects with ongoing development activities and their timelines are listed in the research portfolio presented in FIGURE 4.

With the longer term outlook through to 2036 in mind, it is important to emphasize that the development of future projects depends critically on the ability of the community to explore, develop and assess the utility of new technologies in a manner that is not tied too closely to their final project application. Canada's involvement in new domestic and international projects requires the capacity to develop and utilize new technologies, and early engagement maximizes opportunities for leadership, intellectual property development and subsequent training. However, such generic R&D is not fully supported within the current project-based funding ecosystem, and we highlight the need for additional support for this critical aspect that supports the long-term development and progress of subatomic physics.

SCIENCE RECOMMENDATION
4 — **R&D ACTIVITIES**

We recommend the support of R&D activities for the future development of particle accelerators and detector technology, and the development and use of emerging technologies including novel computational and analysis tools.



TOP: Researchers from the Canadian-Japanese TUCAN collaboration gathered on the experimental floor at TRIUMF. The TUCAN experiment aims to measure the electric dipole of the neutron at an unprecedented level of precision, to provide insights into the puzzle of why there is much more matter than antimatter in the universe. [Credit: TRIUMF]

BOTTOM: Researchers working on the PICO experiment at Canada's SNOLAB. The goal of the PICO experiment is to search for experimental evidence of dark matter particles through possible interactions with nuclear matter that depend on the target nucleus spin. [Credit: SNOLAB]

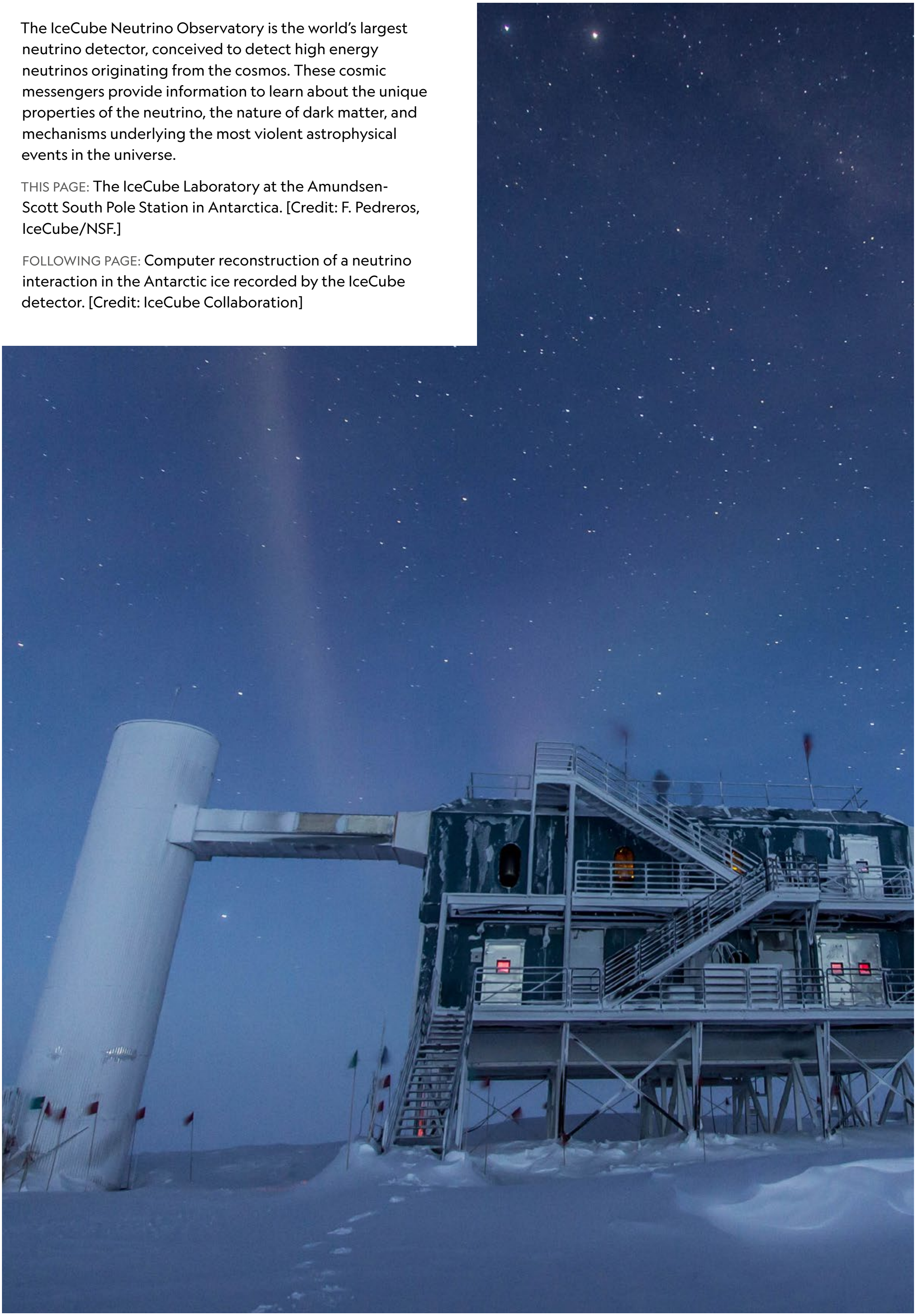
TOP: A researcher working on the ALPHA experiment at the CERN laboratory. The ALPHA experiment uses anti-hydrogen to perform tests of the fundamental CPT symmetry of nature and the universality of gravitational interactions between matter and antimatter. [Credit: TRIUMF]

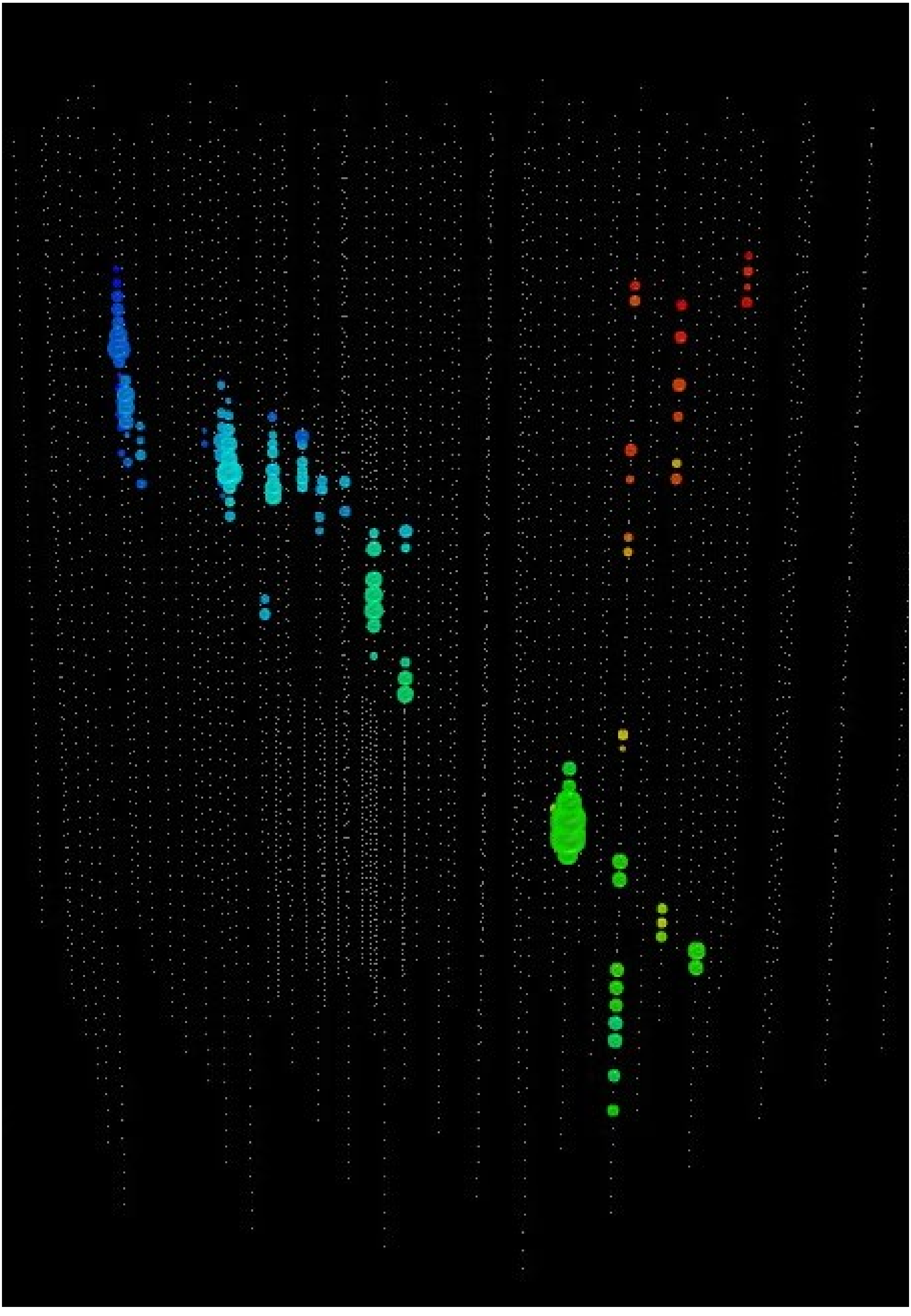
BOTTOM: Researchers at TRIUMF developing novel photodetector modules for the Hyper-Kamiokande experiment. This future world-leading project will provide new insights into the puzzling nature of neutrinos. [Credit: TRIUMF]

The IceCube Neutrino Observatory is the world's largest neutrino detector, conceived to detect high energy neutrinos originating from the cosmos. These cosmic messengers provide information to learn about the unique properties of the neutrino, the nature of dark matter, and mechanisms underlying the most violent astrophysical events in the universe.

THIS PAGE: The IceCube Laboratory at the Amundsen-Scott South Pole Station in Antarctica. [Credit: F. Pedreros, IceCube/NSF.]

FOLLOWING PAGE: Computer reconstruction of a neutrino interaction in the Antarctic ice recorded by the IceCube detector. [Credit: IceCube Collaboration]





SECTION 3 – Realizing the Research Plan

BRINGING THE ambitious plans of the Canadian subatomic physics community to fruition will require support from multiple sources: the major onshore research facilities, TRIUMF, SNOLAB, and the Perimeter Institute; the universities that support the majority of subatomic physics researchers including students and postdocs; supporting infrastructure such as high-performance computing and networking; and the federal funding agencies NSERC and CFI. In addition, the community will need to be cohesive and inclusive to efficiently tackle the science drivers and optimize trainee success.

Canadian Subatomic Physics Community

THE PURSUIT OF the research plan depends first and foremost on the Canadian community of subatomic physics researchers. This community has been successful on the global stage through its organization and a cohesive collaborative approach. It is also truly national, with FIGURE 5 and TABLE 1 showing the geographical distribution of grant-eligible investigators in subatomic physics and its evolution over a time scale of 10 years. The subatomic physics community continues to be vibrant with strength across all regions in Canada, with significant recent growth in Ontario. The renewal of senior investigators in the community, at just over 2% per year, is consistent with the expected retirement rate, but there has recently been additional growth driven in part by the injection of CFREF funding through the McDonald Institute and the consequent hiring of 12 new faculty. Further renewal over the coming decade will be needed. In this regard, the TRIUMF faculty bridge program is effective and such links between universities and national Canadian facilities could be expanded to further support community renewal.

The research profile of the Canadian community has evolved over the past two decades, to reflect progress in the field and evolving science priorities. FIGURE 6 shows the changing research trends within the community over the past 20 years, for example the increased focus on neutrino properties and searches for dark matter, consistent with global trends and the presence of SNOLAB in Canada. Looking forward, given Canada's primary position hosting TRIUMF and the start of operation of several new international facilities over the next decade (e.g. FRIB and FAIR), there are opportunities for growth in the area of nuclear structure.

Subatomic physics is a research field that relies critically on the interplay between theory and experiment for progress. The Canadian theory community has traditionally comprised roughly 30% of the community

FIGURE 5. The Canadian institutions participating in subatomic physics research in 2021.

TABLE 1. The number of NSERC-funded subatomic physics investigators in 2011, 2015 and 2021, broken down by geographical region. The subatomic physics community continues to be vibrant with strength across all regions in Canada, and significant recent growth in Ontario.

Region	2011	2015	2021
British Columbia (BC)	86	88	88
Prairies (AB, SK, NB)	38	38	40
Ontario (ON)	60	66	81
Quebec (QC)	35	31	32
Atlantic (NL, NB, NS, PE)	6	8	8
Total	**225**	**231**	**251**

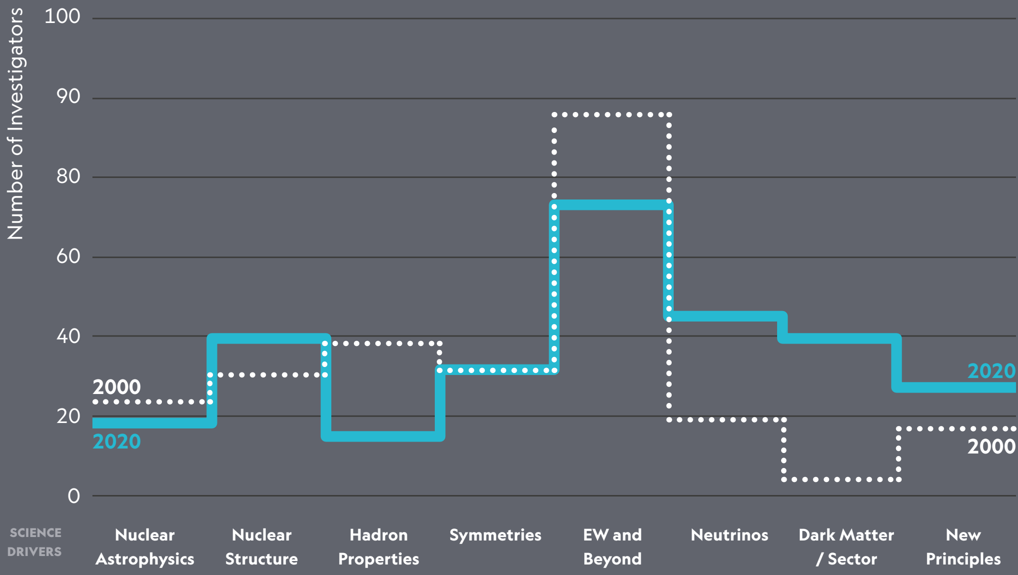


FIGURE 6. The number of NSERC-funded subatomic physics investigators, categorized by the primary science driver of their research, is shown for 2000 and 2020. The research profile of the Canadian community has evolved over the past two decades, to reflect progress in the field and evolving science priorities, for example, with increased focus on neutrino properties and searches for dark matter, consistent with global trends and the presence of SNOLAB in Canada.

TABLE 2. Number of MSc and PhD students supervised per full-time equivalent (FTE) investigator, averaged over the Canadian community, and compared with the corresponding capacity for supervision. There is significant latent capacity in the community for additional graduate student training, presenting a valuable opportunity to maximize both the scientific output from existing investment, and the training of highly-skilled members of the Canadian workforce. In 2020, roughly 60% of graduate students were international.

Year	Grad Students Supervised (Average per FTE)	Grad Student Capacity (Average per FTE)
2015	2.1	3.7
2020	2.6	3.7

as a whole, but the number of NSERC-funded theory investigators has dropped slightly over the past decade to 24%, although the total number of investigators has grown. There is strong support within the broader subatomic physics community for a vibrant theory program, and Canadian theorists have had success and global impact across multiple sub-fields; we therefore see the opportunity for growth in the Canadian theoretical effort. In this regard, it is also vital that the two primary themes of theoretical research — formal development of new principles and structures, and synergistic phenomenology with experiment — be vigorously pursued. All aspects of theoretical research benefit from effective channels for communication and collaboration. Building on the work of existing centres such as the Perimeter Institute, the McDonald Institute, Banff International Research Station (BIRS), TRIUMF and SNOLAB, there are opportunities to further support the theory community with thematic workshop programs that have been successful elsewhere around the world, e.g. at institutions like the Kavli Institute for Theoretical Physics (KITP) and the Institute for Nuclear Theory (INT) in the US, CERN in Switzerland, Mainz Institute for Theoretical Physics (MITP) in Germany, and the European Centre for Theoretical Studies (ECT*) in Italy.

The subatomic physics community is also developing cross-disciplinary collaborations with adjacent research fields, as highlighted in Section 1. This is highly valuable, as such collaborations have traditionally provided fertile ground for both new theoretical ideas and new technological applications. There are important overlaps in science goals with areas of astronomy and cosmology; atomic, molecular, and optical physics; and materials science more generally. Cross-disciplinary collaborations are also driven by overlapping technological tools, and by the development of emerging technologies such as quantum sensing.

Beyond the scientific profile of the subatomic physics community, there is also a need to address broader issues of equity, diversity and inclusion. Canadian society is diverse, and the celebration of this diversity is an important aspect of our national identity. Moreover, equality of opportunity and equitable representation are important drivers for the economy and for scientific progress. A national physics-wide community survey by the CAP EDI committee in 2020, confirmed that diversity within the field does not match the broader society. Indeed, the fraction of NSERC grant holders in the subatomic physics community who are women has evolved from 12% in 2016 to 15% in 2021, but remains well below the level in a number of other STEM fields. The CAP EDI survey indicated that within the wider physics community, these gender disparities are similar at all levels from undergraduate students to faculty, while the disparities for other equity groups were more significant for those in later career stages. While the final results of the survey were not available at the time of writing, the LRP Committee partnered with the CAP EDI survey team to add questions that would allow responses from the subatomic physics community to be separated from those of the broader physics community. Thus, while the initial survey in 2020 provides a baseline, in coming years the longitudinal data from annual surveys will provide valuable input for the community to assess progress toward diversity goals, and the inclusivity of the community overall. In this regard, the efforts led by funding agencies such as NSERC and CFI to ensure that review committees are diverse, and requiring grant applicants to address EDI initiatives explicitly is welcome.

COMMUNITY RECOMMENDATION 5 — **EQUITY, DIVERSITY & INCLUSION**

The Canadian subatomic physics community lacks diversity, as do some other science and technology fields. This lack of representation has many causes, and spans the full career range from graduate students to senior faculty. It is widely recognized that diversity is valuable for the research enterprise, and that a lack of diversity in itself creates a barrier to entry into the field.

- *We recommend the pursuit of further sustained actions aligned with the Tri-Council Dimensions Charter, including regular data-gathering and analysis, targeted initiatives to enhance equity, diversity and inclusion within community activities, and community use of formal committees through the Institutes to support these efforts and/or coordinate with partners.*
- *We recommend that the subatomic physics community promote balanced representation in high visibility leadership roles, as individuals in these positions are important role models, while recognizing that achieving adequate representation can increase the workload for members from under-represented groups.*
- *We recommend that the subatomic physics community promotes inclusion through acknowledgement of the legacy of colonization in Canada, e.g. with the use of land acknowledgements at events held in Canada, consistent with the spirit of the Calls to Action of the Truth and Reconciliation Commission of Canada and of the United Nations Declaration on the Rights of Indigenous Peoples.*

I learned a lot beyond the scope of research by having a female advisor. I saw a glimpse into the extra work that minority faculty members face in universities. My particular advisor was involved in Equity, Diversity, and Inclusion (EDI) and outreach programs. One of these programs focuses on bringing indigenous high school students to the University of Manitoba to experience different science programs with the hope of encouraging those individuals to pursue scientific studies. Participating in these outreach programs gave a better understanding of what other people experience within Canada.

— BRYNNE BLAIKIE (MSC, UNIVERSITY OF MANITOBA, 2022)

The Canadian subatomic physics community includes many undergraduate and graduate students, postdoctoral fellows and research associates, who provide the engine that drives significant research progress and who receive broad training in a technical and international research field. This training is an integral component of the subatomic physics research program. As discussed in more detail in Section 4, one special feature of training within subatomic physics is the highly collaborative and international nature of its activities. The LRP community survey highlighted a significant latent capacity for additional graduate student training (see TABLE 2). This capacity represents a valuable opportunity to maximize both the scientific output from existing investment, and the training of highly-skilled members of the Canadian workforce.

Career development for new faculty and research scientists within Canada is also critical for renewal of the research field. Another outcome of the community survey was that Early Career Researchers (along with all faculty and researchers to a lesser extent) highlighted the ability to recruit talented trainees as the primary barrier to increased research productivity. There are opportunities for the collaborative nature of the field to again provide support, through efficiently sharing of information. It is also recognized that supplemental research funding and time for research can be highly valuable during the early years of a career. The newly rebranded NSERC Arthur B McDonald Early Career Research Fellowship program provides such support; an expansion to match the scale of similar early-career programs in other countries would be valuable within subatomic physics and in other Canadian research fields to kickstart the careers of new faculty and research scientists.

COMMUNITY RECOMMENDATION
6 — **TRAINING & CAREER DEVELOPMENT**

To enable highly qualified personnel to receive training that makes use of the national collaborative structure of subatomic physics research, we recommend the coordination and sharing of training opportunities across Canadian centres, institutes, and universities.

To support early career development, we recommend that Early Career Researchers be supported to quickly gain knowledge of the Canadian subatomic physics research support and funding ecosystem, and be given opportunities to interact broadly with the community.

◂ ▾ ▸

The Canadian subatomic physics community has used self-organization effectively to increase its global impact, and supported the community Institutes which can provide advocacy to government and funding agencies. The LRP processes operating every 5 years are an important part of community organization, but the LRP Committee also sees value in formalizing some existing and successful, but less formal, advocacy activities carried out on a more frequent basis, for example by the community Institutes CINP and IPP.

COMMUNITY RECOMMENDATION
7 — **COMMUNICATION & ENGAGEMENT WITH AGENCIES & GOVERNMENT**

We recommend the formalization (e.g. by CINP and IPP) of a subatomic physics consultation committee for engagement and advocacy to funding agencies and government.

One of the advantages of performing my graduate studies at Simon Fraser University is that I had direct access to TRIUMF. This allowed me to not only preform my own research, but I was able to participate in numerous other experiments. Additionally, I got to observe the day to day workings at TRIUMF that not only include preparations for upcoming experiments, but also preparations for long-term advancements as the beginnings of ARIEL were in the works. My experiences at Simon Fraser and at TRIUMF prepared me for the work that I am doing now as a Project Scientist at Lawrence Berkeley National Laboratory. I know how to utilize all of the resources that are at my disposal. I also recognize the importance of building strong collaborations with fellow researches both locally and at other institutions to create the necessary support to generate a solid scientific program. I feel confident in my career moving forward.

— DR JENNIFER PORE (PHD, SIMON-FRASER UNIVERSITY, 2016), PROJECT SCIENTIST, LAWRENCE BERKELEY NATIONAL LABORATORY, BERKELEY, CALIFORNIA

As an Indigenous student, being funded for the summer has brought me incredible research and learning opportunities such as working to develop theory input for an experiment at Jefferson Lab.

— NICHOLAS O'NEIL (STUDENT, MEMORIAL UNIVERSITY OF NEWFOUNDLAND)

Funding

FUNDING FOR BOTH capital and operations is critical to support the subatomic physics research plan. We characterize the necessary support in the recommendations below.

Capital Funding

The subatomic physics community has been successful in securing significant support for capital investment from CFI programs over the past 15–20 years, and the recent moves to allow for more flexible matching conditions and importantly to regularize the timing of competitions are welcome in facilitating longer-term planning. CFI capital funding for subatomic physics projects has totalled $372M since 2002, 52% of which was in direct support of the major Canadian subatomic physics facilities (TRIUMF, SNOLAB, Perimeter Institute). For 2019–2020, the SAP community received $13.5M, or 3.8% of CFI award funding (*https://innovation.ca/propos/gouvernance/annual-corporate-reports*). This level of support going forward will enable substantial development of new projects in the coming years, as envisaged within the Research Portfolio.

FUNDING RECOMMENDATION
8 — **CFI PROGRAMS**

Support for the development of capital infrastructure through CFI has been instrumental for the development of subatomic physics research in Canada. We recommend continuation of this investment at current annualized levels, which will be critical for the success of the Canadian subatomic physics research plan including many of the proposed future initiatives.

Operations Funding

The success of Canadian subatomic physics research programs depends critically on both access to new capital funding to develop and build new experiments, and the operational support to run the experiments, uncover new science, and train HQP.

The dedicated NSERC SAP Evaluation Section, with its envelope funding model and Project, Individual, MRS and RTI grant programs, has proven to be beneficial to subatomic physics research, which can involve large multi-national teams, and longer timelines. With an appropriate level of coordination and funding, the CFI and NSERC SAP envelope funding structures can successfully support the subatomic physics community in maximizing its research and training impact. The community also appreciates that NSERC acted quickly and decisively to minimize the impact of COVID-19 on Canadian research, implementing valuable extensions and providing recovery funds in 2020 to mitigate the problems associated with lockdowns and disruptions to international activities. This has helped the community weather the global pandemic and continue many of its ongoing research projects.

As noted above, the community has been particularly successful in securing capital support from CFI. However, growth in operations funding has been limited over the past decade. As illustrated in FIGURE 7, operations funding has not kept pace with capital investments in recent years, resulting in a significant change to the ratio of capital to operations funding.

In 2019/20, the NSERC SAP envelope of $26M amounted to 0.8% of all Tri-Council funding, and less than 2% of NSERC funding (*https://www.nserc-crsng.gc.ca/NSERC-CRSNG/Reports-Rapports/plans-plans_eng.asp*). This is well below the 3.8% of CFI funding awarded to SAP projects during this period, and points to limitations on the full exploitation of this capital investment to maximize scientific and training output. Indeed, the SAP envelope has been essentially flat between 2005 and 2015, which significantly eroded operational support after accounting for inflation. Since 2015, the envelope has increased by 23% ($5.5M), helping to alleviate what had become a critical deficit of operational project support. While this increase is welcome and will help to maximize the science impact of prior capital investments, after adjusting for 1.5% inflation, it amounts to approximately flat funding in real terms since 2005.

The success and evolution of the Canadian community, and the development of subatomic physics globally over the past 5 years, justifies further increases in the SAP envelope, as outlined below:

1 Accommodating the transition of twelve CFREF-supported MI faculty into the SAP envelope (requiring $1.2M assuming current per FTE funding). These faculty are all embedded within the subatomic physics community and working on projects with timelines that extend beyond the CFREF program.

2 Operational funding needs:

   a ***Capitalizing on capital investment:*** The Subatomic physics community has continued to be highly successful in securing CFI funding for new experimental infrastructure at both onshore and offshore facilities. To capitalize on these investments, and allow the Canadian community to be internationally competitive, further operational funding is required.

b ***Maximizing training opportunities:*** recent investments in infrastructure at TRIUMF (in particular ARIEL) and SNOLAB (providing full usage of science user space) creates the opportunity to grow the global stature of these facilities, and build broad training opportunities for HQP. This requires sufficient operational support to maximize the science impact of the facilities. Investments in infrastructure at offshore facilities such as CERN and JLab also require full operational support to maximize training opportunities for Canadian HQP.

c ***Developing future flagship projects:*** as indicated in the portfolio, the next decade will see the first operation of several new international nuclear facilities (FRIB, FAIR, EIC), and a new generation of neutrino and dark matter detection experiments. The ability of the Canadian community to take on effective roles in these transformative projects will depend on both NSERC SAP envelope funding for operations and CFI and RTI funds for capital contributions. Full engagement in these projects will require further increases in the envelope into the second half of the decade.

- Full pursuit of the proposed research plan, including (a–c) above require a growth in research capacity and HQP over the next five years. Indeed, there is recognition that the community has the capacity to train 40% more graduate students. With the current number of investigators, and with average student stipends, this requires a $4M increase to the envelope, which would enable a number of the critical developments outlined above.

3 New opportunities funding (e.g to support the RTI program) continues to be very limited, and restoring this fraction of envelope to a baseline of 5% requires additional funding ($1M).

In total, these arguments support growth of the SAP envelope by $6.2M (in current dollars) through 2026. This requested growth target would need to scale in proportion to further growth of the Canadian SAP investigator community.

Operational funding needs associated with 1, 2(a,b), and 3 reflect core components of the research program, and are critical to efficiently maximize the return on investment in ongoing projects, and the infrastructure developed at TRIUMF and SNOLAB and at offshore facilities. Further timely investment will allow for a more robust engagement with new international facilities, e.g. as outlined in 2(c), and other emerging opportunities.

The arguments outlined above, in combination with the science recommendations presented in Section 2, lead to the following recommendations for NSERC SAP envelope funding.

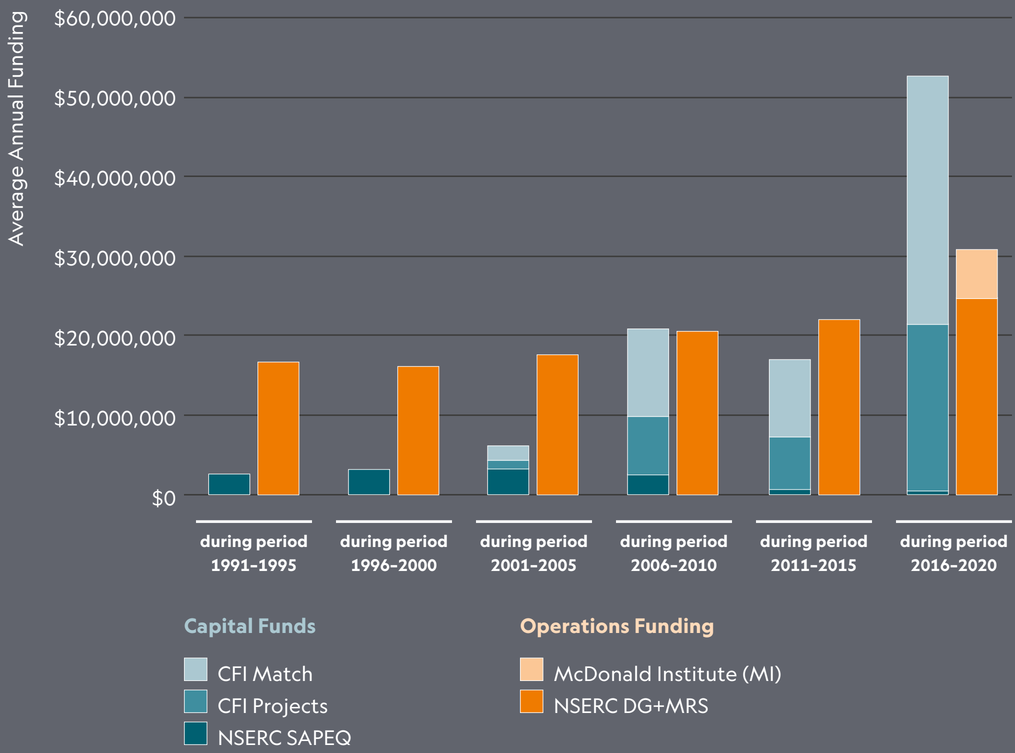


FIGURE 7. Subatomic physics average annual funding is shown in different categories over five year windows, as a function of time. Capital funds (first bar) is contrasted with operations funding (second bar) for each time window. There is no inflation adjustment. The Canada Foundation for Innovation (CFI) grant and matching contribution amounts do not include the major CFI awards in support of TRIUMF ARIEL infrastructure, the SNOLAB facility and the Perimeter Institute. The McDonald Institute (MI) funding portion corresponds only to the funds allocated in direct support for research. Operations funding has not kept pace with capital investments in recent years, resulting in a significant change to the ratio of capital to operations funding.

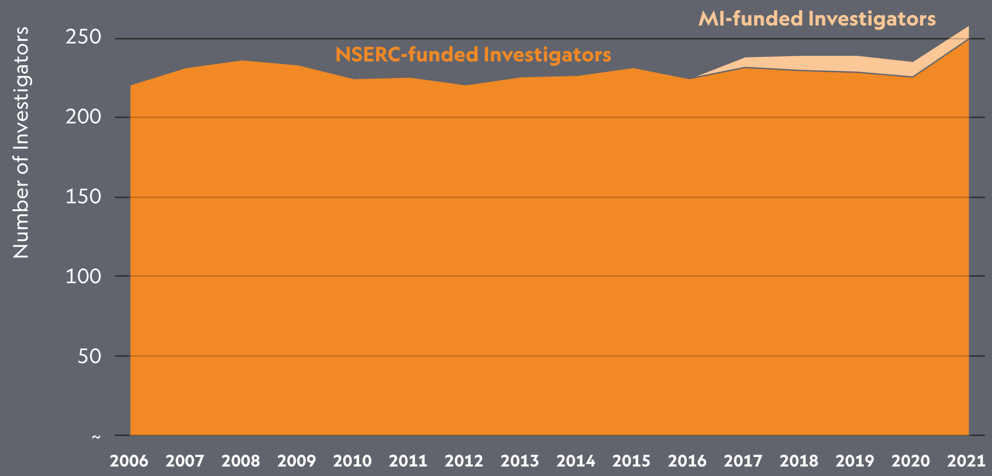


FIGURE 8. The number of subatomic physics investigators over the past 15 years whose research is funded by NSERC and the McDonald Institute (MI). With the McDonald Institute CFREF funding coming to an end, MI-funded faculty will require NSERC operational support.

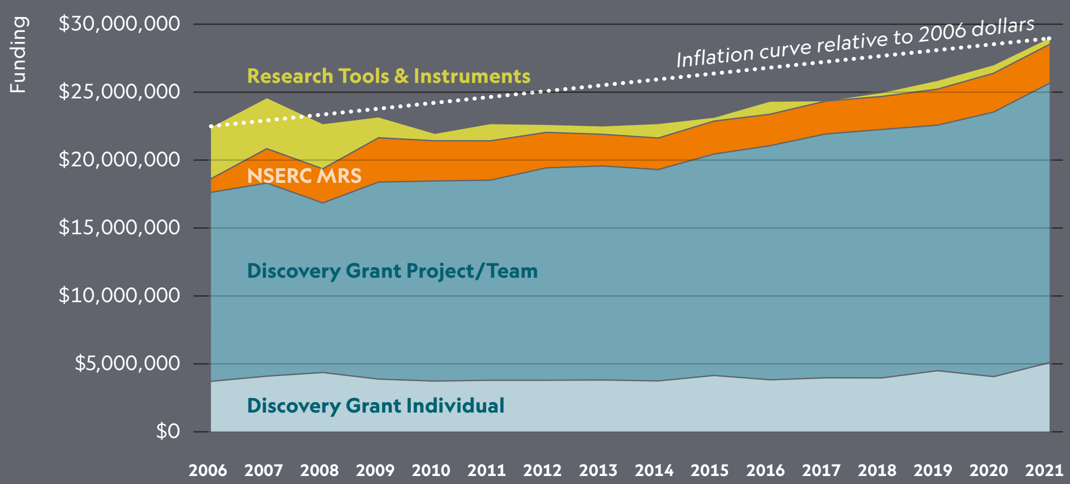


FIGURE 9. NSERC funding allocated to different programs within the subatomic physics envelope within the past 15 years. Support for recurring operations costs (within the Discovery Grant programs and the MRS program) has grown in recent years. However, over 15 years, this growth has now just caught up to inflation. Meanwhile, the portion of funds allocated to capital funding through the Research Tools and Instruments (RTI) program has decreased to a minor fraction of the envelope. CFI has become the primary source of capital funding. Note that the increase to the envelope in 2007 corresponds to a one-time out-of-envelope contribution to SNOLAB operating funds.

FUNDING RECOMMENDATION
9 — **NSERC SUBATOMIC PHYSICS ENVELOPE**

To maximize the impact of current and future investments, and to take advantage of future science opportunities, growth of the NSERC subatomic physics envelope is required for operational support.

- *We recommend retention of the NSERC subatomic physics envelope structure, and its programs, which have been instrumental for the operational funding of subatomic physics research.*
- *We recommend growth of the NSERC subatomic physics envelope by $6.2M in 2021 dollars over the next five years to ensure that the Canadian program remains globally competitive. This growth is required for several reasons: to accommodate the transition of McDonald Institute faculty requiring NSERC support; to utilize the full community capacity for training of highly qualified personnel and maximize the return on capital investment; and to ensure sufficient availability of funds for small infrastructure projects and the development of future science opportunities.*
- *We recommend continued support for all the program categories available within the NSERC subatomic physics envelope; this includes the Major Resources Support (MRS) program, which critically supports the efficient collaborative use of unique technical resources in the development and construction of new instruments, and the Research Tools and Instruments (RTI) program which provides important support for detector and accelerator development.*
- *We recommend the monitoring and protection of the NSERC subatomic physics envelope fraction allocated to fund theory investigators. In addition, the minimum award threshold should not be below the level of funding required to support graduate training, as is the case in other Physics Evaluation Sections.*

Infrastructure and Technical Support

IN ADDITION TO capital and operations funding, support for key infrastructure is required to implement the research plan.

The major Canadian subatomic physics research laboratories and institutes provide critical value for the community, and are a core component of Canada's infrastructure. The national laboratories, TRIUMF for nuclear and particle physics and accelerator-based science, and SNOLAB, for deep underground astroparticle science, along with the Perimeter Institute for Theoretical Physics, have global stature and play an important role in positioning Canada in the global subatomic physics community. These physical facilities are supported by virtual institutes, the Canadian Institute for Nuclear Physics (CINP) and the Institute of Particle Physics (IPP), with a membership that collectively encompasses the Canadian subatomic physics investigator community. Most recently, an injection of funds from the CFREF program facilitated the establishment of the McDonald Institute (MI), which supports the sub-community involved in underground astroparticle science.

Starting with the major experimental laboratories, TRIUMF and SNOLAB, recent investments (discussed in Section 3) will enable growth in their scientific output, and this will require sustained operational funding to fully exploit those prior investments. TRIUMF has recently transitioned from a joint venture to a not-for-profit corporation, and continues to rely on five-year federal funding allocations to support the majority of its operations and programs. SNOLAB continues to develop, and has been well supported through the CFI MSI program with provincial matching in Ontario. The flexibility in the MSI program is valuable. However, to fully develop as a global research laboratory, further flexibility to support research-focused technical staff would be valuable.

FUNDING RECOMMENDATION
10 — **SUPPORT FOR CANADA'S WORLD-LEADING CENTRES**

Canada's large-scale centres for subatomic physics research have global stature, and provide competitive advantages in pursuing high-priority scientific programs.

We recommend maintaining strong support for Canadian centres (TRIUMF, SNOLAB, Perimeter Institute) so that they remain at the forefront of research worldwide.

The efficient sharing of resources within the subatomic physics community has been important for its success. In part, this includes the community-led research supports such as MRS technical support labs across the country, and the IPP Research Scientist program. The latter program, which funds eight senior experimental research scientists who are able to lead Canada's participation in major international projects, has been critical in enabling Canada to take on leadership roles in these projects. This value is highlighted clearly in the IPP Brief to the LRP, which emphasizes that the Canadian particle physics community considers the IPP Research Scientist program to be its highest funding priority.

FUNDING RECOMMENDATION
11 — **IPP RESEARCH SCIENTIST PROGRAM**

The IPP Research Scientist program has had a major impact on Canada's leadership and contributions to international projects.

We recommend maintaining full support for the IPP Research Scientist program.

The McDonald Institute, currently supported by the CFREF program, has been a significant addition to the Canadian subatomic physics community since the last LRP. It has supported the growth of the sub-community focused on underground and sub-surface observatories seeking to study neutrinos and dark matter. In particular, this funding has enabled the development of significant technical support programs at partner institutions, and it would be valuable to maintain this support once the CFREF funding comes to an end.

FUNDING RECOMMENDATION
12 — **ARTHUR B MCDONALD INSTITUTE**

The existence of the Arthur B McDonald Institute and its research support and outreach programs has added considerable value to the community. However, its CFREF funding is coming to an end.

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We recommend that in addition to growth of the NSERC subatomic physics envelope to support operational costs, new mechanisms be identified to fund and maintain continuity of the research and technical support programs provided by the Institute.

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Subatomic physics has for many years been one of the leaders in the development of research computing and networking, with the world wide web famously developed at CERN, and machine learning tools used for many years in simulation and data analysis. The ongoing and future computing needs are hard to overstate, with increasing data rates and the need for high precision modelling and simulation. The subatomic physics community has been a major user of Compute Canada services, and relies on CANARIE for networking infrastructure, along with dedicated support services such as the MRS-funded HEPNET program. With Canadian research computing infrastructure undergoing a period of restructuring, members of the community have been fully engaged in the development of the new Digital Research Alliance (formerly NDRIO). It is important that these new structures that emerge have the appropriate organization and sufficient resources to address the specific needs of the subatomic physics community over the coming decade.

FUNDING RECOMMENDATION
13 — **CANADA'S DIGITAL RESEARCH INFRASTRUCTURE**

All components of digital research infrastructure (e.g. Compute Canada, CANARIE) are critical to the success of subatomic physics research.

We recommend that CANARIE continues to be funded by the Canadian federal government for operation of the national research network and key links to our international partners. Further, we recommend that critical computing infrastructure provided by national computing organizations (Compute Canada and the Digital Research Alliance (formerly NDRIO)) continue to be strongly supported by federal and provincial governments, at a level appropriate to address the needs of the subatomic physics research community.

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The longer-term 15-year outlook for this LRP brings into focus the importance of enabling research and development that will facilitate Canada's participation in new domestic and international project opportunities that may emerge in coming years. The development and application of emerging technologies is critical to assess their utility in enabling progress in subatomic physics. Efforts that are not directly tied to a specific project are valuable, but difficult to fund within the current ecosystem.

FUNDING RECOMMENDATION
14 — **FUNDING FOR R&D ACTIVITIES**

New research opportunities are enabled by the development of novel instruments and technologies. This development relies upon the ability to explore technological frontiers that are beyond the scope of individual subatomic physics experiments.

We recommend that appropriate mechanisms be identified to efficiently fund modest and timely investments in generic R&D activities that have the potential to address the scientific goals of subatomic physics research.

Research Policy

CANADA'S SUBATOMIC PHYSICS research program makes use of major onshore facilities such as SNOLAB and TRIUMF, but also utilizes the best facilities worldwide to conduct research. These facilities include CERN in Switzerland, which hosts the LHC; J-PARC and KEK in Japan, which host the T2K and Belle II experiments, respectively; JLab in the US, which is one of the major nuclear user facilities globally; and a number of other labs worldwide.

The participation of the community in large-scale global projects is an intrinsic feature of subatomic physics research, and in this era of growing security concerns it is important that this openly collaborative aspect be maintained. However, the need for large-scale collaboration also highlights some structural concerns with the Canadian research ecosystem. In particular, while NSERC and CFI provide valuable support for the development of projects and project components up to a threshold of $10–20M, there is less structure in place to facilitate Canada's involvement in larger-scale projects, or the associated in-kind contributions that may be needed for participation in international laboratories. Within Canada, examples of potential large-scale initiatives over the coming decade include an expansion of the science cavern space at SNOLAB, and the development of a storage ring at TRIUMF. It is also highly valuable for those labs to continue enabling the participation of Canadians at international offshore labs, for example by providing in-kind contributions such as those for the LHC accelerator complex that supports Canada's participation at CERN and involvement in the ATLAS experiment. This role is enhanced by the continuing development of world-leading infrastructure and expertise at these labs. However, it is notable that support by the labs for offshore engagements has often required an ad hoc negotiation process.

The above concerns highlight the fact that establishing a national structure to oversee the full life-cycle development and management of large-scale projects with total costs of over $50M, and a single point of contact to help develop and manage international agreements, would greatly assist the community in engaging fully in emerging large-scale science opportunities over the coming decade.

POLICY RECOMMENDATION
15 — **SUPPORT FOR LARGE-SCALE SCIENCE ENDEAVOURS**

Coordination of the capital costs and operational funding over the life-cycle of large-scale (≳ $50M) science endeavours and infrastructure projects is difficult within the current ecosystem.

We recommend the formation of a new administrative structure to provide this coordination (as articulated in Recommendation 4.7 of Canada's Fundamental Science Review 2017: Investing in Canada's Future, *http://sciencereview.ca).*

POLICY RECOMMENDATION
16 — **CANADIAN OFFICE FOR INTERNATIONAL RESEARCH ENGAGEMENT**

Subatomic physics research is intrinsically global, and increasingly requires complex multinational agreements.

We recommend the identification of an office in Canadian government responsible for engaging with the international community with the goal of advancing major new science initiatives.

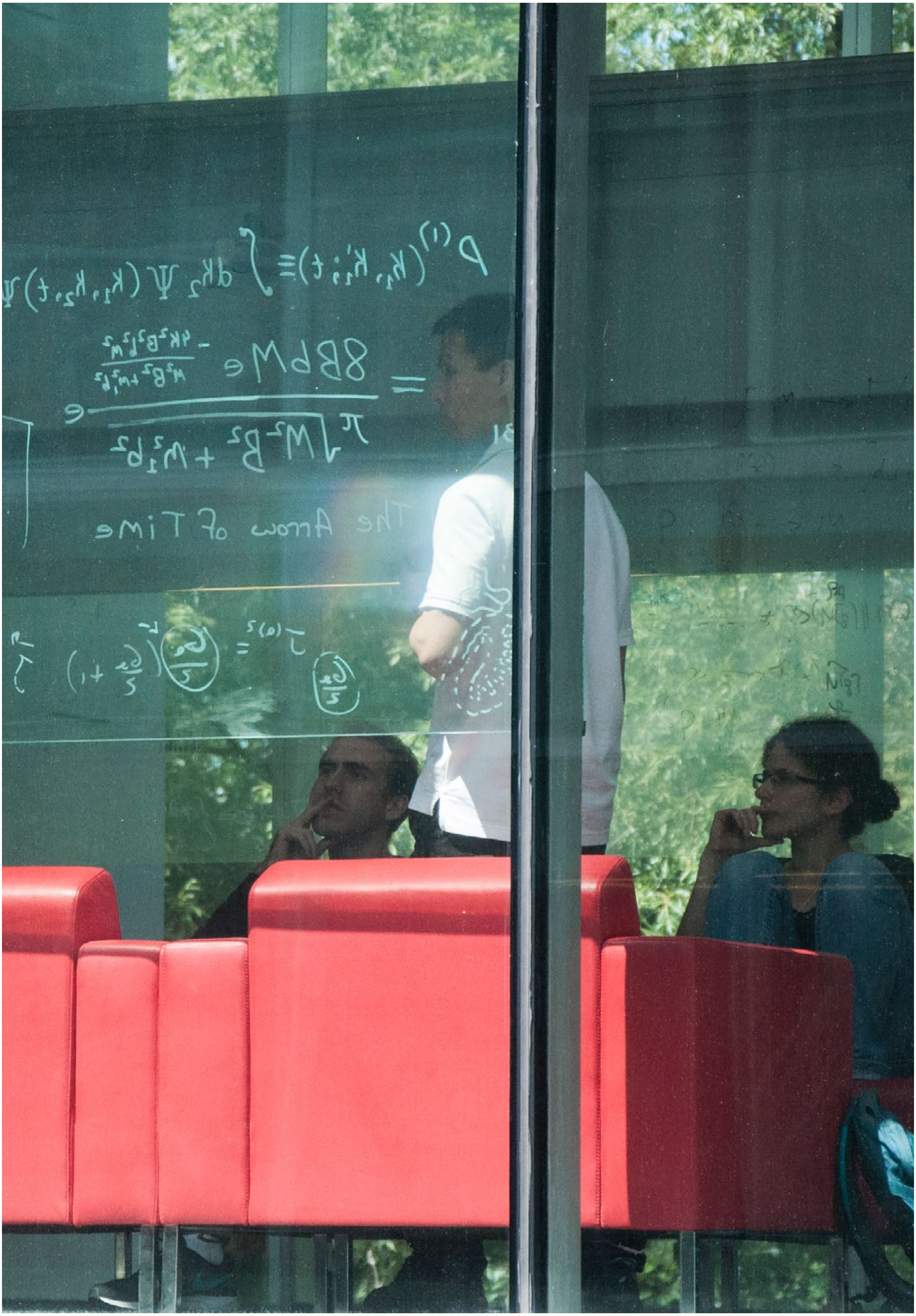
Studying subatomics physics presented many challenges that helped me learn mechanical, coding, research, analysis and problem solving skills. But perhaps most importantly it showed me that I am a capable learner. This gives me confidence in my competence as I move forward in another career path. More practically, I was able to engage in science communication projects throughout my Master's degree that gave me experience which directly relates to my current position. Being supported in my science communication projects gave me soft skills that complemented the harder skills I got in physics.

— LIA FORMENTI (MSC MCGILL 2021),
ONLINE EVENTS COORDINATOR, LET'S TALK SCIENCE

THIS PAGE (TOP & BOTTOM): The Perimeter Institute's "Inspiring Future Women in Science" conference mixes science talks with discussion of the rewards, challenges, and possibilities of a STEM career. [Credit: Perimeter Institute]

The Perimeter Institute for Theoretical Physics, in Waterloo, Ontario, is a world-leading and internationally recognized center for fundamental research, graduate training, and educational outreach.

THIS PAGE AND FOLLOWING PAGE: Researchers interacting at the Perimeter Institute for Theoretical Physics. [Credit: Perimeter Institute]


The Arrow of Time

SECTION 4 –
Benefits to Society

THE IMPACT of Canadian subatomic physics research and development activities goes beyond individual scientific endeavours, with many far-reaching contributions to Canadian society. Progress in subatomic physics inspires and enriches our culture while simultaneously pushing the boundaries of technology. Indeed, subatomic physics improves our fundamental understanding of the physical world while seeding innovation through the development of enabling technologies like particle accelerators, advanced electronics, and communication and data analysis techniques, and training technically skilled people that help Canada to compete in the knowledge-based economy. Subatomic physics also connects people across cultures and across national and societal boundaries as they ask and seek to answer fundamental questions while fostering the development of an innovative knowledge-based economy. Progress in subatomic physics also leads to new commercial opportunities that exploit subatomic physics technology or discoveries.

The different levels of impact for subatomic physics research can be visualized with an onion-layer model, with the core subatomic physics community at the centre and the layers representing relevance for increasingly broader sectors of society:

- Collaborating scientific fields
- Training for the knowledge economy
- Technological applications
- Commercial opportunities
- Environmental impact
- Cultural benefits

The first of these impact layers, relating to cross-boundary science, was discussed in Section 1. We consider the broader areas of impact and the return on investment in subatomic physics research for Canada in this section.

> *My training and my years of experience as a researcher have been part of my transition to industry, both in terms of tools (programming, scientific equipment, basic physical notions) and related learning (presentation of results to peers, leadership, ability to work independently). Especially in the field of data science, the particle physics profile is very well suited to the demands of industry with the integration of machine learning in research.*

— DR ANDRÉE ROBICHAUD-VÉRONNEAU
(MSC, MCGILL 2005; RESEARCH ASSOCIATE, MCGILL 2014–2017), DATA SCIENTIST, CIENA

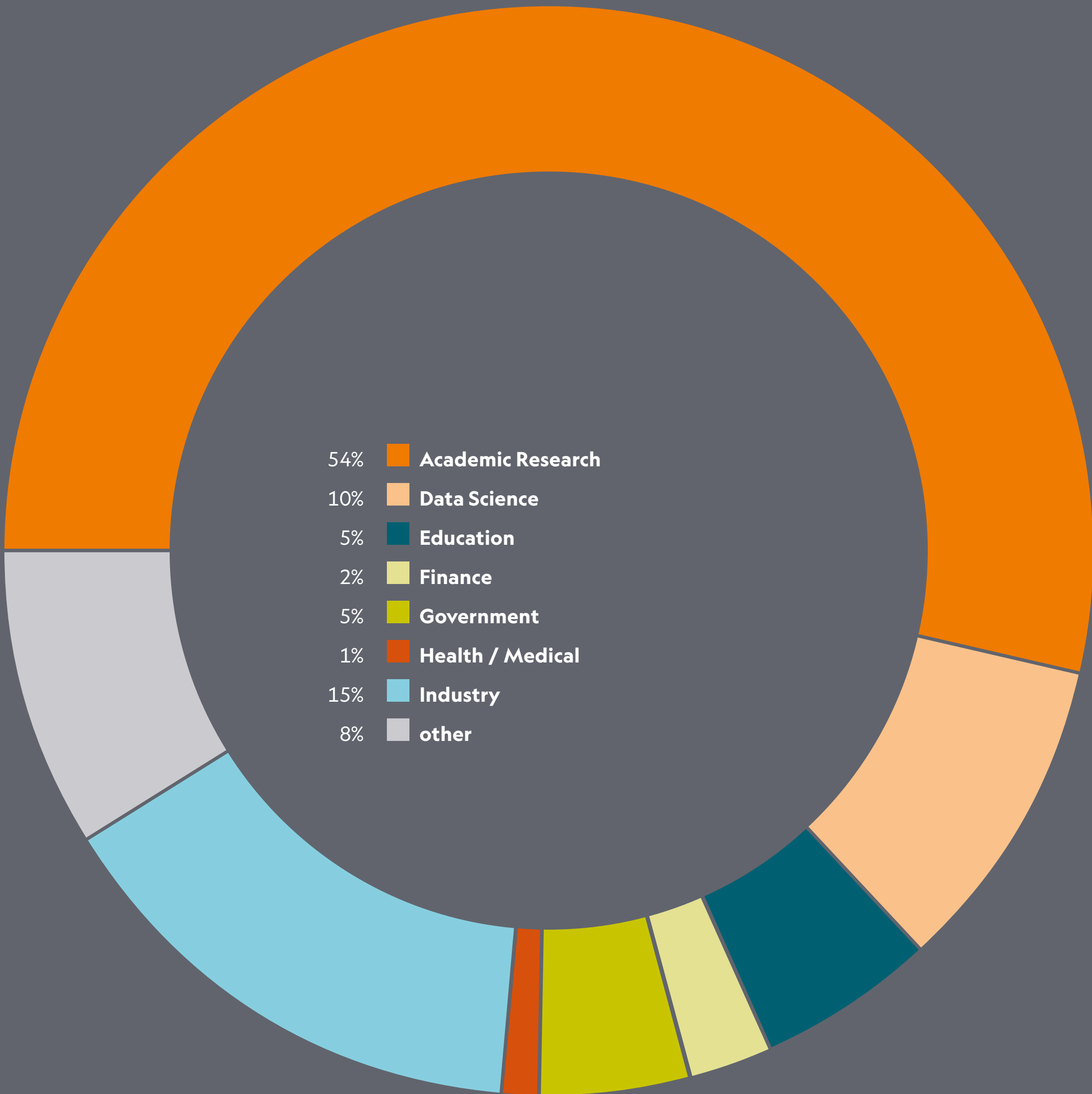


FIGURE 10. Career plans of current subatomic physics graduate students, from the LRP community survey with a sample size of 106. Similar outcomes for past graduate students were observed from a survey conducted in developing the IPP Brief to the LRP.

Training for the Knowledge Economy

AN IMPORTANT ASPECT of the subatomic physics program is the training of highly qualified personnel (HQP). The scope of HQP training within the field is rich and diverse, spanning the gamut from theoretical constructs, data acquisition and analysis, hardware design and fabrication, testing and refinement, reporting and promotion, and project management. Training of HQP in subatomic physics is realized through hierarchical learning utilizing both undergraduate and graduate students and postdoctoral fellows within university or institute settings. The students participate in both group and independent activities based on the common themes of a particular research group. This learning process is augmented with participation in conferences or workshops or other training opportunities. For example, programs like the TRIUMF Summer Institute or the Canadian Tri-institute Summer School on Elementary Particle Physics offer unique opportunities for students to learn and network.

Subatomic physics research has many unique and distinctive features that provide exceptional opportunities for training and preparation for specific fields in the knowledge economy:

- The scope, size and international nature of collaborative networks through which research is performed.
- The efficient sharing of global research resources and funding.
- The breadth of technical and non-technical skills and expertise acquired (e.g. from theory, complex data analysis, to instrumentation and software development, and system integration).

Graduate students in subatomic physics indeed move on to a range of technical careers, as summarized in FIGURE 10.

Technological Applications and Commercial Opportunities

FROM THE BROAD economic use of accelerator technology to the birth of the internet, subatomic physics has had a technological impact on society in many ways. Direct impacts include the spin-off applications of technology developed for subatomic physics research. Recent examples can be found in areas ranging from medical imaging, to security and wireless networking. Less direct, but more pervasive evidence of impact can be found in the diagnosis and treatment of disease through isotope production, radiation therapies and diagnostics, nuclear power, nuclear waste management, material science, and detector development applicable to dosimetry in medical and space applications. Medical physics infrastructure supported by nuclear physics is also a key ingredient in the development of radio pharmaceuticals. This progress is spurred on by the high level of technological innovation demanded for success in subatomic physics research. The community is often required to develop its own unique instrumentation to make progress in tackling the science drivers, which then finds broader applications.

Over the past five years Canadian researchers have advanced techniques that can save lives while fuelling an economy of tomorrow. In response to the global pandemic, the Mechanical Ventilator Milano (MVM) Collaboration, an international collaboration of national nuclear and particle physics laboratories from Italy, Canada, the United States, and other countries, has leveraged its collective expertise in the design of gas handling and electronic control systems to develop an economical ventilator for both mandatory and assisted ventilation. The simplicity of the design, which is made possible by the MVM's sophisticated control system, allows easily available parts to be utilized and for rapid manufacturing. Guided by medical experts and in cooperation with industrial partners Vexos and JMP Solutions in Canada, the MVM Collaboration has succeeded in a remarkably short period to design, develop, build, and certify a safe ventilator in response to the COVID global crisis. In Canada the effort was led by Nobel Laureate Art McDonald, involving team members from TRIUMF, CNL Chalk River, SNOLAB and the McDonald Institute. The MVM development is a prime example of how the expertise of subatomic physicists who are trying to unravel the mysteries of the universe can be effectively utilized to the benefit of society in tackling its other grand challenges.

The subatomic physics community has a history of mutually beneficial collaboration with a number of industry sectors. As is apparent from the MVM example above, the globally connected subatomic physics laboratories and collaborations provide a valuable

> *I'm currently a PhD candidate in the Netherlands using a supercomputer to simulate the atmospheric boundary layer and large-scale wind farms. However, my first research projects were in subatomic physics, with NSERC/IPP/CERN summer awards. Though the physics I do now is more applied, I wouldn't be here without the foundation that I received at the Grenfell campus of the Memorial University of Newfoundland. The professors always had an open door, put in the time, and genuinely wanted us to succeed. Not only did I gain research and computing skills which I use to this day, but I also learned that great things were not out of reach.*
>
> — JESSICA STRICKLAND (BSC MEMORIAL UNIVERSITY, GRENFELL), PHD CANDIDATE AT UNIVERSITY OF TWENTE, NETHERLANDS

resource, with the expertise and capacity to pivot and rapidly address new priorities from genesis to commercialization. Several other novel collaborations are developing technologies for societal benefit, particularly in the medical sphere. A few examples are listed below:

- Researchers at TRIUMF and SFU are investigating the use of thorium target material for medical isotope production.
- Researchers at TRIUMF and Guelph University are teaming up to improve range verification in proton/hadron cancer therapy via gamma-ray spectroscopy techniques.
- Researchers at McGill University and Université de Sherbrooke are collaborating to study the possibility of using the light emission properties in liquid Xe developed for rare event searches (nEXO) for medical imaging in PET.

Beyond health research, investigations in the environmental sector are also being pursued. Examples include the following:

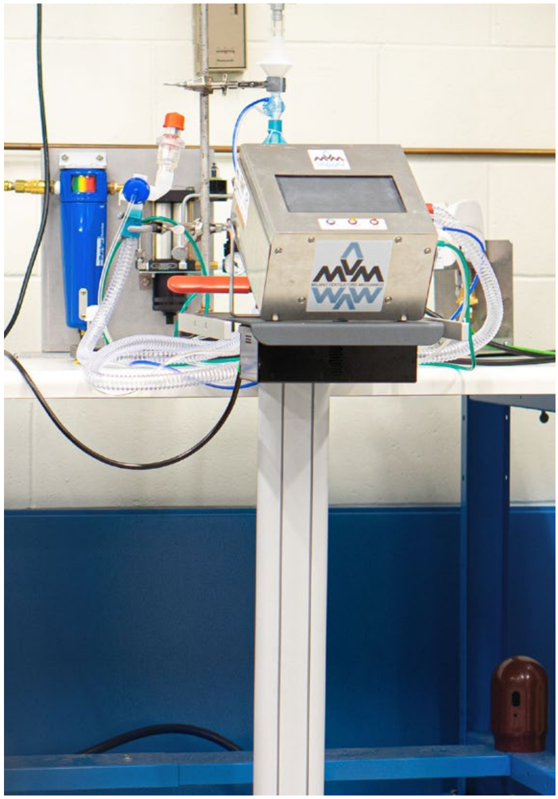
- Researchers at TRIUMF and University of Calgary are studying water & atmospheric flow/tracking through radioactive isotope tracing.
- MOLLER collaboration members are working with researchers in the biosciences to investigate the growth behavior of fungi and other plants under extreme environmental conditions by working on the customization of MOLLER electronics design to produce a small DAQ system that can be deployed in a remote area, to monitor environmental data.
- SNOLAB and Laurentian University are part of a R&D effort led by the CNSC to improve technologies for the verification of nuclear non-proliferation treaties — spherical proportional counters (SPCs) developed by NEWS-G could lead the way to a compact and non-intrusive technology to monitor nuclear reactors and international nuclear safeguarding.

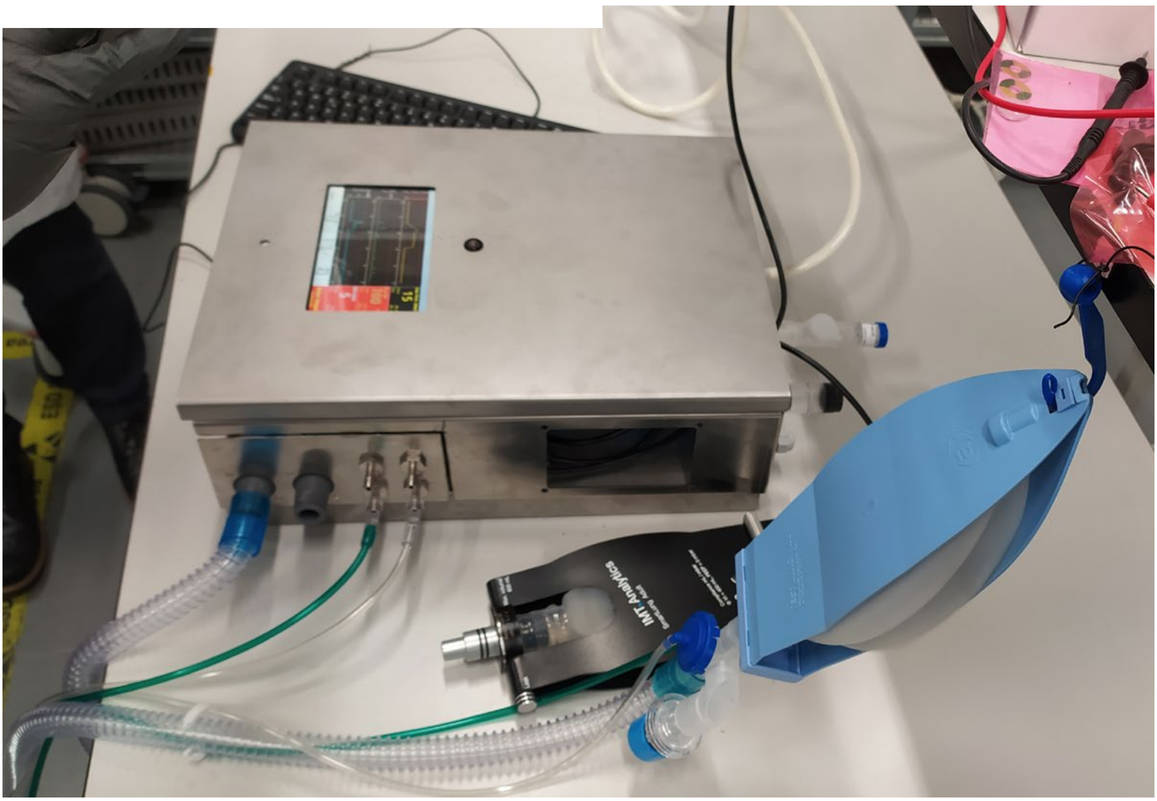
While cutting edge R&D is the life-blood of subatomic physics, opportunities for societal or commercial benefit need incubation for broader impact. Commercialization opportunities are often apparent, driven by the development of new technology and applications, but there are also a number of challenges. Timescales for research may be significantly longer than those that are tolerable for return on investment within industry. There is also limited time for university faculty and research staff to develop contacts and nurture relationships with industry. The exacting performance requirements for cutting edge subatomic physics research may also go beyond what is most viable commercially. However, in some cases these stringent requirements push the boundaries of manufacturing, and lead to new and more efficient processes; the current ATLAS silicon tracker upgrade is an example. Further work in addressing these incubation challenges will enhance opportunities for broadening the impact of subatomic physics. Such incubation support may be provided by university technology transfer offices, and in technical transfer centres like TRIUMF Innovations, the commercialization arm of TRIUMF. As one example, through TRIUMF Innovations, IDEON is moving forward in offering muon detectors for better diagnosis of mining deposits. Technology transfer can enhance incubation not just by linking cutting-edge science and technology to tangible business opportunities, but also by nurturing the connections and industry partnerships necessary for success.

THIS PAGE (TOP & BOTTOM): In response to the global COVID-19 pandemic, the MVM Collaboration, an international collaboration of subatomic physics laboratories from Italy, Canada, the United States, and other countries, leveraged its collective expertise to develop a ventilator that can provide both mandatory and assisted ventilation. The simplicity of the design, which is made possible by the MVM's sophisticated control system, allows for ease of availability of parts, and rapid manufacturing in different countries.

Guided by medical experts and in cooperation with industrial partners Elemaster in Italy as well as Vexos and JMP Solutions in Canada, the MVM Collaboration succeeded — in record time — to design, develop, build and certify a safe ventilator. In Canada the effort was led by Nobel laureate Art McDonald, involving team members from Canadian Nuclear Laboratories Chalk River, McDonald Institute, SNOLAB, and TRIUMF. In September 2020, the MVM received approval by Health Canada under the Interim Order and Vexos started to deliver the 10,000 units that have been ordered by the Federal Government of Canada.

The rapid development of this project was only possible due to around the clock work by a large team spread across nine time zones, enabling effective hand-off and progress on the various development tasks. The MVM development is a prime example of how the expertise of nuclear and particle physicists — who are trying to unravel the mysteries of the foundations of the Universe — can be effectively mobilized in real time to help tackle our major global societal challenges. [Credit: MVM Collaboration]





Environmental Impact

IN CONSIDERING FUTURE technological applications, it is also important to recognize that the global nature of subatomic physics research, a field that relies critically on international cooperation and transparency, also has non-negligible environmental impacts. While air travel for collaboration and experimental work at off-site laboratories remains important to the field, a silver lining of the COVID-19 pandemic is that the full value of online collaboration and communication tools was realized and may therefore provide more flexibility in modes of collaboration in the future. The research facilities used in subatomic physics research are also significant users of power, for example to drive magnets, RF amplifiers, and cryogenics plants, and this applies broadly also to the researcher community through the wide use of computing resources. However, this impact is mitigated through global collaboration, which allows the development and operation of only a few large-scale international facilities worldwide. In addition, the accelerator community for example continues to pursue more efficient technologies and power delivery systems to reduce their global footprint as well as to explore better energy recovery schemes.

It is also important to emphasize the opportunities that subatomic physics research, and its associated large-scale research facilities, may provide in pointing the way to new green energy sources, such as generation IV nuclear reactors, small modular reactors, and plasma-driven fusion technologies. There are potential applications of the accelerator technology developed to enable subatomic physics research for mitigating the environmental impact of energy production; for example in the handling of long-lived radioactive materials, which require careful decommissioning. There are active efforts to explore nuclear transmutation which would have broader global impacts for green nuclear energy. For example, high power proton linear accelerators can be used to drive sub-critical nuclear power plants or to treat spent nuclear fuels through transmutation. High intensity electron accelerators could also be used to treat flue gases produced in industrial power plants. Thus the subatomic physics community and its global laboratories are positioned to support the development of technologies that mitigate climate impact in the future.

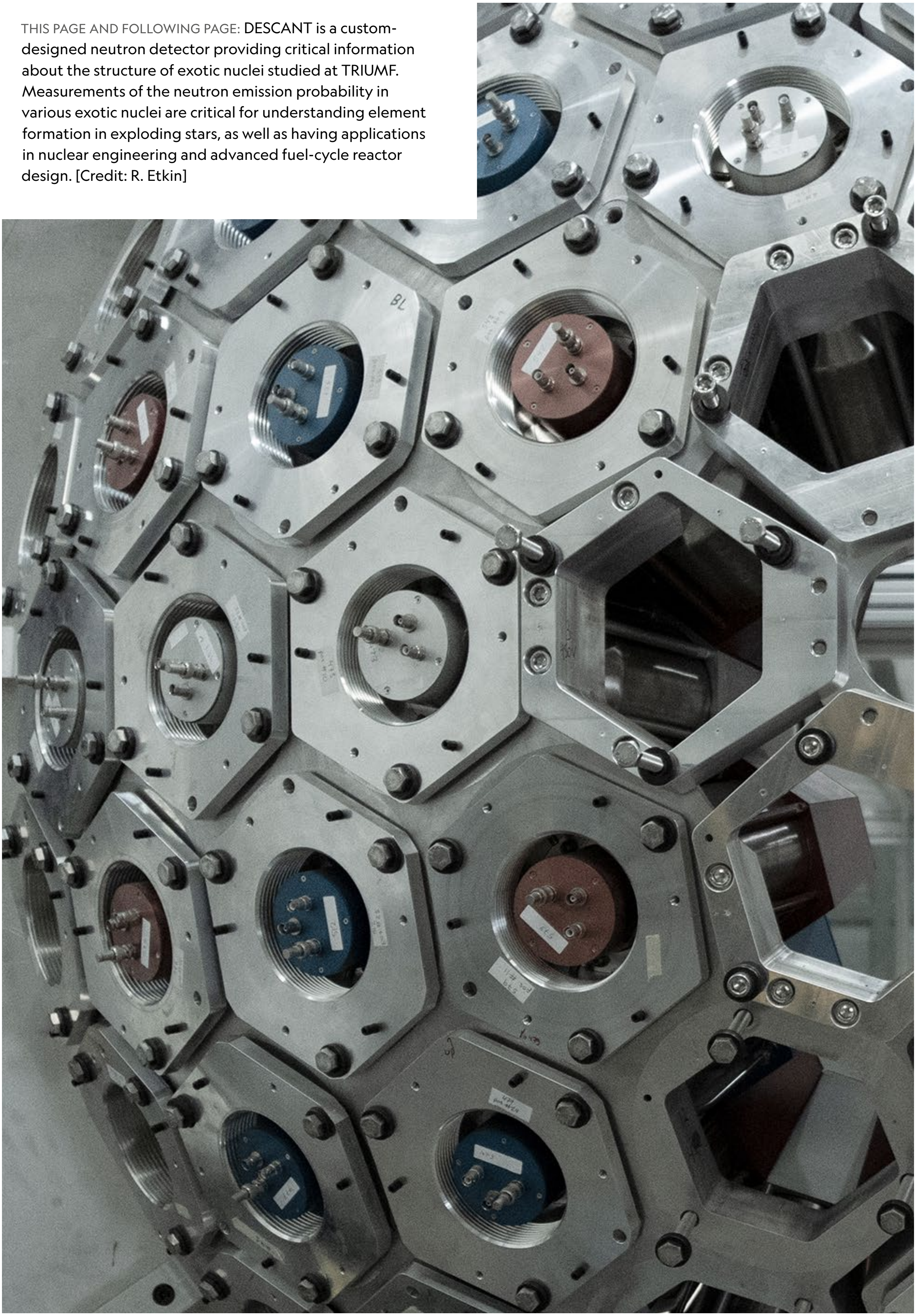
Cultural Benefits

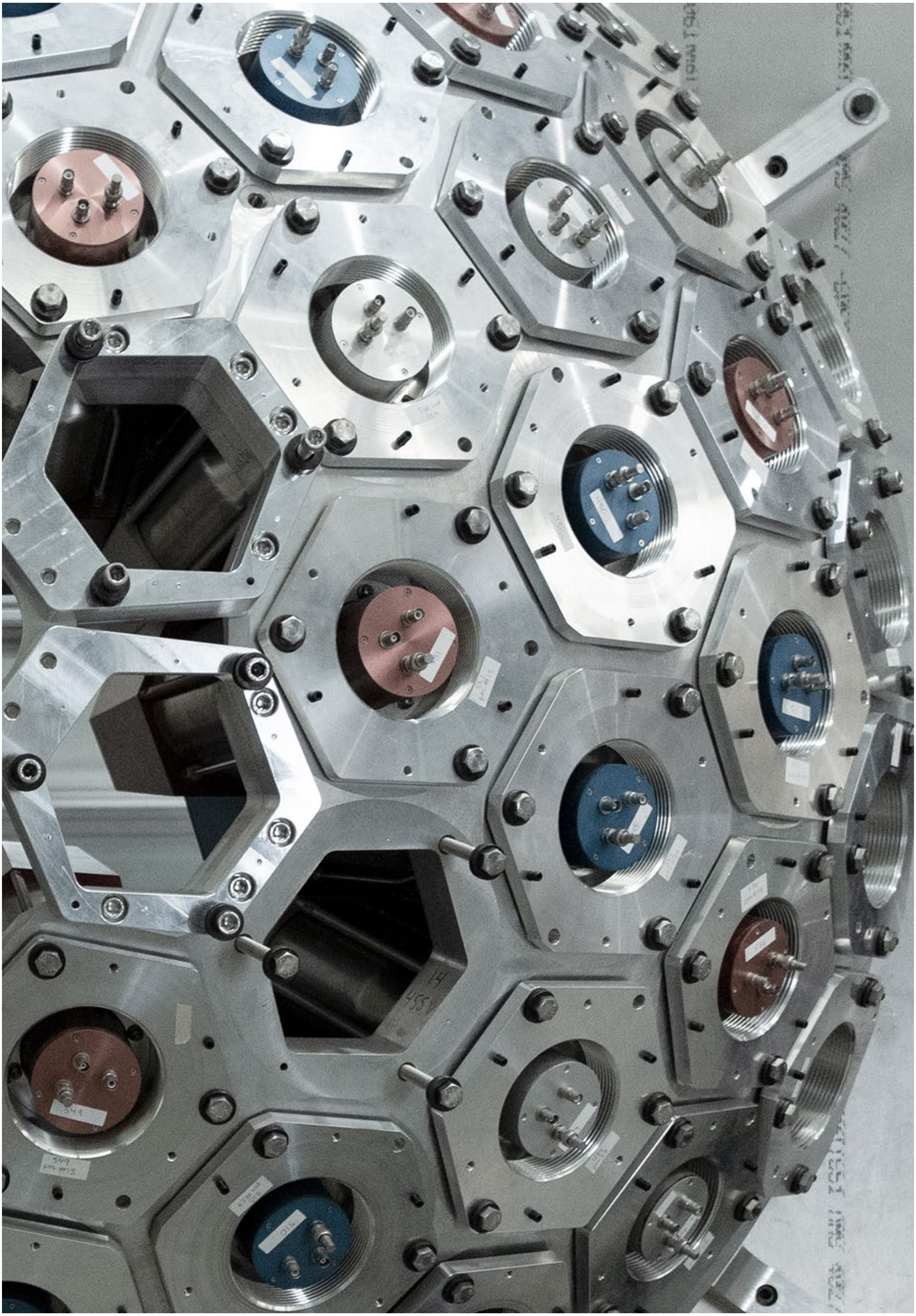
SUBATOMIC PHYSICS RESEARCH has a long-lasting impact on society, through the inspiration provided by gaining a greater collective understanding of the basic laws of nature, and through its highly collaborative global structure. The excitement generated by new discoveries in the field can serve to inspire Canadians and can be leveraged to attract Canadian youth towards dynamic careers in science and technology.

Canada has been fortunate to have had several recent winners of the Nobel Prize in Physics; from Art McDonald in 2015 for the discovery of neutrino oscillations and his leadership role with the SNO experiment in Sudbury, Ontario, to Donna Strickland's award in 2018 for high-intensity laser physics, and Jim Peebles' award in 2019 for multiple contributions to theoretical cosmology.

Beyond these significant peer accolades that reinforce the stature of Canadian subatomic physics endeavours and enhance public interest and excitement, public outreach is at the core of subatomic physics activities to support public education and interaction with the community. Outreach is also critical to EDI, in reaching out to under-represented groups, and seeking to engage the Canadian public and future students in subatomic physics. The major centres, TRIUMF, SNOLAB, the Perimeter Institute, the McDonald Institute, and universities have outreach programs that are an essential core service to help foster impact at all levels — the general public, elementary and high school students, and undergraduate students. It is important to recognize that outreach efforts take time and effort. There are opportunities for the community to efficiently support further outreach by partnering with these major centres and other community organizations. Such efforts are important to further the understanding of subatomic physics, and our growing knowledge of the universe, within Canadian society.

THIS PAGE AND FOLLOWING PAGE: DESCANT is a custom-designed neutron detector providing critical information about the structure of exotic nuclei studied at TRIUMF. Measurements of the neutron emission probability in various exotic nuclei are critical for understanding element formation in exploding stars, as well as having applications in nuclear engineering and advanced fuel-cycle reactor design. [Credit: R. Etkin]





Glossary

ALPHA (Antihydrogen Laser PHysics Apparatus)
A set of experiments at the CERN Antiproton Decelerator trapping and studying the properties of antihydrogen atoms (incorporates ALPHA-3 and ALPHA-g).

ARIEL (Advanced Rare IsotopE Laboratory)
A project to enhance TRIUMF's capabilities to produce rare isotope beams and to showcase new Canadian accelerator technology.

ATLAS (A Toroidal LHC ApparatuS)
An experiment at the CERN Large Hadron Collider, one of the two general-purpose detectors at the Large Hadron Collider, primarily detecting the collision products of proton-proton collisions.

Belle II
A B-hadron physics experiment at the SuperKEKB electron-positron collider in Japan.

BRIKEN (Beta-delayed neutron studies at RIKEN)
A large 3He-long counter neutron detection array with an implantation detector which will take data at the Riken Nishina Center until 2021.

CANARIE
CANARIE operates and evolves the national backbone of Canada's ultra-high-speed National Research and Education Network (NREN), providing the national and international networking for Canada's subatomic physics community.

CANREB (CANadian Rare-isotope facility with Electron-Beam ion source)
A CFI-funded project that will improve the purity of rare ion beams delivered by ARIEL to ISAC.

CERN (the European Organization for Nuclear Research)
International laboratory for nuclear and particle physics located on the French-Swiss border near Geneva.

CFI (Canada Foundation for Innovation)
Created by the Government of Canada in 1997, CFI makes investments in state-of-the-art research facilities and equipment in a wide variety of scientific disciplines.

CINP (Canadian Institute of Nuclear Physics)
A formal organization of the Canadian nuclear physics research community to promote excellence in nuclear research and education, and to advocate the interests and goals of the community both domestically and abroad. It gathered input from the Canadian nuclear physics research community for this document.

CPT (Charge, Parity, Time)
The combined Charge, Parity and Time symmetry is assumed to be an exact symmetry of nature at the fundamental level.

CREX (Calcium Radius EXperiment)
Experiment at JLab to measure the neutron radius of ^{48}Ca.

CUTE (the Cryogenic Underground Test Experiment)
An underground facility at SNOLAB for testing and characterizaton of SuperCDMS crystals and other cryogenic detectors.

DEAP/DEAP-3600 (Dark matter Experiment using Argon Pulse shape discrimination)
A dark matter experiment searching for direct detection of weakly interacting massive particles using scintillation in 3.3 tonnes of liquid argon.

DESCANT (DEuterated SCintillator Array for Neutron Tagging)
A 70-element neutron detector array used at ISAC.

DOE (Department of Energy)
The United States Department of Energy, which operates a number of national laboratories across the USA.

DRAGON (Detector of Recoils And Gammas Of Nuclear reactions)
A detector designed to measure the rates of nuclear reactions important in astrophysics, based at ISAC-I.

EDM (Electric Dipole Moment)
A relative displacement of positive and negative charge in an object. Permanent electric dipole moments are forbidden for fundamental particles by time reversal violation.

EIC (Electron-Ion Collider)
A new DOE nuclear physics user facility under construction at Brookhaven National Lab.

EMMA (ElectroMagnetic Mass Analyzer)
A device to study the products of nuclear reactions involving rare isotopes at ISAC-II.

EXO (Enriched Xenon Observatory)
An experiment to measure neutrinoless double beta-decay in 136Xe. The EXO-200 experiment is located at the WIPP facility in New Mexico, USA. nEXO is under development for installation at SNOLAB.

FAIR (Facility for Antiproton and Ion Research)
An accelerator facility for studying nuclear structure and nuclear matter, presently under construction as an upgrade of the GSI facility in Darmstadt, Germany.

FRIB (Facility for Rare Isotope Beams)
A new DOE user facility for nuclear science on the campus of Michigan State University in the USA with first experiments in 2022.

FrEDM (Francium Electric Dipole Moment)
A future experiment to measure the electric dipole moment in francium at TRIUMF ISAC-I.

FrPNC (Francium Parity Non-Conservation)
An experiment to study atomic parity non-conservation in francium, based at ISAC-I.

GlueX (Gluonic Excitations Experiment)
An experiment seeking to identify hybrid mesons with explicit gluonic degrees of freedom at Jefferson Lab Hall D.

GSI (GSI Helmholtz Centre for Heavy Ion Research)
A research center in Darmstadt, Germany.

GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei)
A detector at ISAC-I for studying nuclear decays at high resolution.

HALO (Helium And Lead Observatory)
A long-term, low-cost, high-livetime, and low-maintenance dedicated supernova detector running at SNOLAB.

HL-LHC (High-Luminosity LHC)
The high-luminosity running phase of the LHC planned to begin in 2027.

HQP (Highly Qualified Personnel)
Personnel obtaining advanced skills as a result of NSERC-funded research, including students, postdocs and technicians.

Hyper-K (Hyper-Kamiokande)
A neutrino observatory, the successor to Super-Kamiokande, being constructed near Kamioka, Japan to study the physics of neutrinos and rare processes such as proton decay.

IceCube (IceCube Neutrino Observatory)
A particle detector at the South Pole encompassing a cubic kilometer of ice instrumented with a 3D array of photo-detectors.

ILC (International Linear Collider)
A proposed electron-positron linear particle collider with a planned initial collision energy of 250 GeV, and possible upgradable up to 1 TeV.

IPP (Institute of Particle Physics)
A formal organization that promotes Canadian excellence in particle physics research and advanced education. It gathered input from the Canadian particle physics research community for this document.

IRIS (ISAC Charged Particle Reaction Spectroscopy Station)
A rare-isotope reaction spectroscopy station utilizing reactions with a frozen (solid) hydrogen and deuterium targets.

ISAC (Isotope Separator and ACcelerator)
A rare isotope accelerator facility, based at TRIUMF. There are two experimental halls, ISAC-I and ISAC-II.

JLab (Jefferson Lab)
The Thomas Jefferson National Accelerator Facility, located in Newport News, Virginia.

J-PARC (Japan Proton Accelerator Research Complex)
Joint project between KEK and the Japan Atomic Energy Agency, which hosts the proton accelerator used in the T2K experiment (and future Hyper-K experiment).

KEK (High Energy Accelerator Research Organization and National Laboratory)
A Laboratory located in Tsukuba, Japan, specialising in neutrino and B-hadron physics.

KEKB (KEK B-physics)
An Asymmetric Electron-Positron Collider for B-hadron Physics located at KEK. It hosts the Belle II experiment.

LBNF/DUNE (Long-Baseline Neutrino Facility/ Deep Underground Neutrino Experiment)
Dual-site experiment for neutrino science and proton decay studies, hosted by Fermilab and the Sanford Underground Research Facility.

LEGEND
A collaboration to search for neutrinoless double beta decay formed with the merger of the Gerda and Majorana collaborations. LEGEND-200 is an experiment under construction at Gran Sasso Laboratory in Italy. LEGEND-1000 is a proposed detector comprising 1000 kg of germanium crystals.

LHC (Large Hadron Collider)
A proton and heavy ion collider at CERN which hosts the ATLAS, CMS, LHCb, and ALICE experiments.

MAMI (Mainz Microtron)
An electron accelerator facility, located on the campus of the Johannes Gutenberg University of Mainz, Germany.

MOLLER (Measurement Of a Lepton-Lepton Electroweak Reaction)
An experiment to measure the parity-violating asymmetry in electron-electron (Moller) scattering at Jefferson Lab.

MRS (Major Resources Support)
An NSERC program to facilitate the effective access by Canadian academic researchers, working in the field of subatomic physics, to major and unique national or international (based in Canada) experimental or thematic research resources by financially assisting these resources to remain in a state of readiness for researchers' to use.

NA62
Experiment at the CERN Super Proton Synchrotron to measure the rare kaon decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$.

NDRIO (New Digitial Research Infrastructure Organization)
Organization tasked with re-structuring Canadian academic research computing. The organization was renamed the Digital Research Alliance of Canada in late 2021.

NEWS-G (New Experiments With Spheres - Gas)
Collaboration developing gaseous spherical proportional counters for multiple particle detection purposes. NEWS-G @SNOLAB is an experimental direct search for dark matter, currently operating at SNOLAB.

nEXO (The next phase of the Enriched Xenon Observatory)
A next-generation experiment searching for neutrinoless double-beta decay in 5 tonnes of liquefied xenon enriched in ^{136}Xe, proposed for SNOLAB.

NSERC (Natural Sciences and Engineering Research Council of Canada)
An agency of the Government of Canada that supports university students in their advanced studies, promotes and supports discovery research, and fosters innovation by encouraging Canadian companies to participate and invest in postsecondary research projects.

PI (Perimeter Institute for Theoretical Physics)
Centre for scientific research, training, and educational outreach in foundational theoretical physics based in Waterloo, Ontario.

PICO
A collaboration formed merging the Picasso and COUPP experiments that searched for direct detection of dark matter with bubble chambers at SNOLAB. The current detector, PICO-40L, operates with 40 L of superheated liquids. A 500 kg version, PICO-500, is under construction at SNOLAB.

P-ONE (Pacific Ocean Neutrino Experiment)
A proposed neutrino telescope in the deep waters of the Pacific Ocean off Vancouver Island, BC, supported by Ocean Networks Canada infrastructure.

QCD (Quantum ChromoDynamics)
The theory describing the fundamental interactions between quarks and gluons.

RHIC (Relativistic Heavy Ion Collider)
Heavy-ion collider at Brookhaven National Laboratory in the USA.

RIB (Rare Isotope Beam)
A beam used in studies of nuclear structure and nuclear reactions of astrophysical importance.

RIBF (Rare Isotope Beam Factory)
A user facility for nuclear science, located at RIKEN Nishina Center, Japan.

RIKEN (The Institute of Physical and Chemical Research)
Japan's largest comprehensive research institution that performs research in a diverse range of scientific disciplines, including physics, chemistry, medical science, biology and engineering.

RTI (Research Tools and Instruments)
NSERC program to financially support research tools and instruments.

SAP (SubAtomic Physics)
The broader field of nuclear and particle physics, comprising all knowledge taking place at scales smaller than that of the atom.

SBC (Scintillating Bubble Chamber)
Experiment proposed for SNOLAB to search for dark matter and coherent neutrino scattering.

SLAC (Standford Linear Accelerator)
SLAC National Accelerator Laboratory is a US Department of Energy Office of Science laboratory operated by Stanford University.

SM (Standard Model)
The Standard Model of elementary particle interactions.

SNO (Sudbury Neutrino Observatory)
A heavy-water based solar neutrino physics experiment that was located deep underground in Sudbury which solved the solar neutrino problem. Professor Arthur McDonald shared the 2015 Nobel Prize for his direction of SNO.

SNO+
An experiment at SNOLAB whose objective is to study neutrinoless double beta-decay and lower-energy solar and geo-neutrinos using a liquid scintillator instead of heavy water in the SNO detector.

SNOLAB (Sudbury Neutrino Observatory Laboratory)
A deep underground facility in Sudbury, Ontario, specializing in neutrino physics and the search for dark matter.

SoLID (Solenoidal Large Intensity Device)
A high luminosity, large acceptance detector proposed for Jefferson Lab Hall A that makes use of the former CLEO solenoid magnet.

SRF (Superconducting Radio Frequency)
Acceleration of charged particles via the use of superconducting cavities operating in the radio frequency range. Examples include the ISAC-II and ARIEL accelerators at TRIUMF and the Continuous Electron Beam Accelerator at Jefferson Lab.

SuperCDMS (Cryogenic Dark Matter Search)
A dark matter experiment under construction at SNOLAB, and successor to previous generations of CDMS experiments, that will search for the direct detection of weakly interacting massive particles using cryogenic silicon germanium detectors.

T2K (Tokai to Kamioka)
A long baseline experiment from J-PARC to the Super-Kamiokande neutrino detector in Japan to study the physics of neutrino oscillation.

TIGRESS (TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer)
A detector at ISAC-II for studying nuclear decays at high resolution.

TITAN (TRIUMF's Ion Trap for Atomic and Nuclear science)
An ion trap facility at ISAC for high-precision mass measurements of rare isotopes.

TRINAT (TRIUMF Neutral Atom Trap)
A device to trap and study the radioactive decays of neutral atoms, based at ISAC-I.

TRIUMF
Canada's national laboratory for particle and nuclear physics and accelerator-based science.

TUCAN (TRIUMF Ultra-Cold Advanced Neutron)
A CFI-funded facility to study ultra-cold neutron properties at high precision, under development at TRIUMF.

UCN (Ultra-Cold Neutrons)
Neutrons with a kinetic energy of approximately 300 neV, or velocities $\simeq$ 7 m/s.

THIS PAGE: Graduate student Satbir Kaur (St. Mary's University) working at the Radioactive Isotope Beam Factory in Japan. [Credit: R. Kanungo]

"During my PhD at Dalhousie University and Saint Mary's University, my opportunity to work at international labs (GSI and RIKEN) helped me master critical thinking and problem-solving skills. It helped me master data analysis, data visualization and presentation skills. All these skills are very helpful in projects at my current job as a data scientist at iWave on Prince Edward Island."

Planning Process

Terms of Reference

Context

The Canadian subatomic physics community establishes its scientific, and thus funding, priorities through five-year Long-Range Plans (LRP). These plans advise the Canadian subatomic physics research community and relevant stakeholders on priorities for both current and future endeavours. The most recent Long-Range Plan covered the period 2017–2021, in addition to providing an assumption-based forecast for into 2026. A new LRP exercise is to be conducted. The new plan will be in effect from 2022 through 2026, with its scope extending through 2036. A renewal of this 2022–2026 plan will occur before 2026. The Canadian Subatomic Physics Long-Range Plan 2022–2026 is jointly supported by the Institute of Particle Physics (IPP), the Canadian Institute of Nuclear Physics (CINP) and the Natural Sciences and Engineering Research Council (NSERC). The additional stakeholders, TRIUMF, SNOLAB, the Perimeter Institute and the Canada Foundation for Innovation (CFI), are supportive of this process.

Committee

The LRP process will be driven by the Canadian subatomic physics community. A LRP Committee will be asked to review this community's input and to formulate the Long-Range Plan. The LRP Committee will be composed of an appropriate number of experts who will cover the main sub-disciplines of subatomic physics in Canada, including both experimental and theoretical aspects: nuclear physics, nuclear astrophysics, physics of elementary particles and fields, and particle astrophysics. The LRP Committee will be co-chaired by senior members of the research community with an extensive knowledge of the Canadian and international subatomic physics research environments. The membership may have some overlap with that of the previous LRP Committee to ensure continuity.

The following representatives from the LRP commissioning bodies will be non-voting members on the LRP Committee.

- Director of the Institute of Particle Physics
- Executive Director of the Canadian Institute of Nuclear Physics
- NSERC Team Leader working with subatomic physics
- Co-Chairs of the NSERC Subatomic Physics Evaluation Section for 2020–2021

In addition, the LRP Committee will invite ex officio members who will be non-voting observers and resources for the other members:

- TRIUMF Director
- SNOLAB Director
- Perimeter Institute representative
- CFI Director of Programs working with subatomic physics

The LRP Committee may choose to hold certain closed sessions without the presence of ex officio members.

Mandate

Taking into account (i) the ever increasing internationalization of projects and collaborations in addressing the fundamental questions of subatomic physics, (ii) the concurrent requirement to maintain and further develop world-class domestic research programs and infrastructure, (iii) the established expertise and strengths of the Canadian community and (iv) the recognition of the fact that the Canadian subatomic physics community cannot be involved in all research endeavours, the Committee is asked to identify subatomic physics scientific ventures and priorities that should be pursued by the community on a five to fifteen year horizon and that would ensure continuous Canadian global scientific leadership. Budgetary estimates, both for new capital investments as well as for operations, must be provided as well, including funding ranges for prioritized endeavours. These ranges should include funding levels that would allow for a restrained, yet efficient, contribution to the ventures, as well as levels that would enable a more extensive contribution.

The Committee's assessment will be based on a broad consultation with the Canadian subatomic physics community. The Committee will have to assess the feasibility, technical readiness and risks associated with particular endeavours. It is crucial that such an assessment be made through a fair and rigorous process.

The Committee is also asked to consider and discuss factors that affect the subatomic physics community and to make recommendations on how to possibly lessen any negative impacts they may have, or enhance any positive ones. Examples of such factors include, but are not limited to, various funding opportunities, the relationship between funding agencies and other organizations, the activities of national research organizations, and the international context.

The report should address Equity, Diversity and Inclusion as well as supporting early career researchers within the context of the subatomic physics research community.

Process and Timeline

The LRP Committee membership recruitment will be completed by Spring 2020, and a kick-off meeting will be held immediately after. NSERC staff will coordinate membership recruitment in consultation with the Committee Co-Chairs as well as CINP and IPP.

CINP and IPP will be tasked to prepare briefs for the LRP Committee. These briefs must summarize the scientific vision and priorities put forward by the sub-communities they represent and serve, including both experimental and theoretical facets. Overall recommendations may also be included in the briefs. It is expected that each institute will broadly consult with the sub-communities through various formats and ensure a fair and rigorous process. The briefs are to be submitted to the LRP Committee and to NSERC no later than December 1, 2020.

The Institutes must ensure that the briefs are available to the entire community through their public Web sites. Eventual responses to the briefs by individuals or organizations would be accepted. Throughout the process, the LRP Committee may also solicit additional input from various sources, as it sees fit.

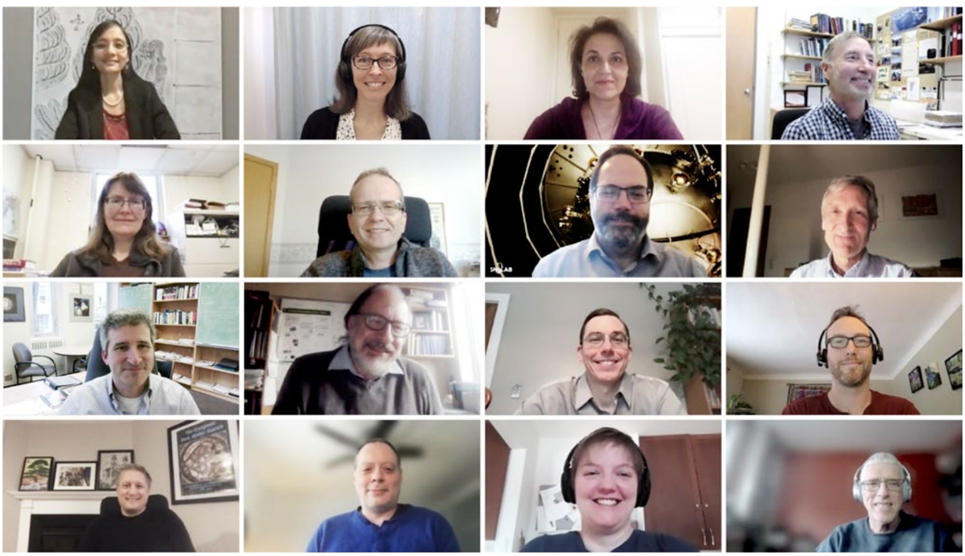
The LRP Committee will hold public consultations (town hall meetings) in early 2021, after receiving the briefs. Face-to-face or phone meetings of the Committee will then be held up to the Summer of 2021.

Deliverables

The LRP Committee will submit its final report to NSERC, CINP and IPP no later than September 30th, 2021. The report will be publicly released, thereafter, in both official languages.

Confidentiality and Conflicts of Interest

All members must strictly comply with the Code of Ethics and Business Conduct for Members of NSERC Standing and Advisory Committees. Moreover, for the purpose of this exercise, a member will be considered to be in a situation of conflict of interest during a discussion on prioritization of a specific endeavour that would directly benefit the member or the member's organization.



LRP Committee Personnel

Committee Members

Eckhard Elsen	CERN, Switzerland
Chris Jillings	SNOLAB, Canada
Rituparna Kanungo	St. Mary's University, Canada
Bob Laxdal	TRIUMF, Canada
Augusto Macchiavelli	LBNL, USA
Juliette Mammei	University of Manitoba, Canada
Jeff Martin	University of Winnipeg, Canada
Adam Ritz (co-chair)	University of Victoria, Canada
Niki Saoulidou	University of Athens, Greece
Kate Scholberg	Duke University, USA
Brigitte Vachon (co-chair)	McGill University, Canada
Alex Wright	Queen's University, Canada

Ex-officio Members & Observers

Cliff Burgess	Faculty, Perimeter Institute (PI)
Emily Diepenveen	Team Leader, NSERC (until Jan 1, 2021)
Jens Dilling	Assoc Lab Director, Physical Sciences, TRIUMF
Olivier Gagnon	Manager, John R. Evans Leaders Fund, CFI
Thomas Gregoire	NSERC SAPES (co-chair)
Jeter Hall	Research Director, SNOLAB (from April 8, 2021)
Garth Huber	Executive Director, CINP
Kevin Lapointe	Team Leader, NSERC (from Jan 1, 2021)
Alison Lister	NSERC SAPES (co-chair)
Tony Noble	Scientific Director, McDonald Institute (MI)
J. Micheal Roney	Director, IPP
Nigel Smith	Executive Director, SNOLAB (until April 8, 2021)

As described in the Terms of Reference, all LRP Committee members were required to comply with the Code of Ethics and Business Conduct for Members of NSERC Standing and Advisory Committees. Moreover, for the purpose of this planning exercise, members were considered to be in a situation of conflict of interest during a discussion on prioritization of a specific endeavour that would directly benefit the member or the member's organization.

To manage conflicts of interest, all members declared their interests in writing when joining the committee, or when those interests changed. These declared interests were circulated confidentially to all LRP Committee members for transparency. Members were requested to remain silent during specific discussions for which they had a declared conflict of interest.

Timeline

THE PLANNING PROCESS conducted by the Subatomic Physics LRP Committee is outlined in this section. It is important to highlight that all stages of the process in 2020 and 2021 were conducted during the COVID-19 pandemic, and existing safety measures required that all meetings of the LRP Committee and all public townhall consultations with the community were online and conducted via videoconference.

The LRP planning process involved extensive community consultation and engagement. The nuclear and particle physics sub-communities presented input to the LRP Committee early in the process through comprehensive positions papers submitted by the Canadian Institute of Nuclear Physics (CINP) and the Institute of Particle Physics (IPP). The LRP committee also engaged regularly with the community through a survey, multiple online townhall meetings, and by soliciting feedback throughout the process on draft recommendations and initial drafts of the final report. The use of videoconferencing technology provided broad accessibility to members of the community Canada-wide, including graduate students, and allowed the LRP Committee to hold a number of thematic townhalls, to further expand the consultation and community engagement phase of the planning process.

The LRP Committee met every 2 to 3 weeks throughout the planning exercise via videoconference, and the main stages in the process are summarized on the following pages.

Launch of the SAP LRP process

June 11, 2020 — CINP-IPP joint session at the CAP Congress

June 22-23, 2020 — CINP Townhall meeting

July 15, 16, 21, 2020 — IPP Townhall meeting

Environmental Scan

September / October 2020

- Analysis of historical funding data from NSERC and CFI
- Analysis of national long-range plans:
  - Canadian SAP LRPs from 2006, 2011 and 2017
  - Canadian Astronomical Society LRP 2020
  - US P5 Report 2014, and the ongoing SNOWMASS process for 2020
  - US Nuclear Science LRP 2015
  - European NuPECC LRP 2017
  - European Particle Physics Strategy Update 2020

SAP LRP Community survey

- November 2020 — 370 grant-holder and HQP respondents to survey questions on research activities, EDI and outreach

CINP and IPP position papers

- December 1, 2020 — Position papers submitted to the LRP by the Canadian Institute of Nuclear Physics (CINP) and the Institute of Particle Physics (IPP). These comprehensive documents summarize the existing research activities and future plans and priorities of those Canadian subatomic physics sub-communities.

Community Consultation

Topical Townhall 1: Subatomic Physics Community

- February 16, 2021 — Education, Training and Careers — moderated Q&A session with the community
- February 17, 2021 — Equity, Diversity & Inclusion, Early Career researchers, Community organization — moderated Q&A session with the community

Topical Townhall 2: Subatomic Physics Science Opportunities

- March 8, 2021 — Science Planning and Opportunities — international panel discussion and moderated Q&A session with the community
- March 10, 2021 — Subatomic Physics Connections: Interfacing to other fields and society — panel discussion and moderated Q&A session with the community

Emerging themes consultation document (released April 16, 2021)

LRP Community Townhall

- April 20, 2021 — Canadian subatomic physics in 2021 — summary of funding data and community survey
- April 21, 2021 — Feedback on emerging themes — moderated Q&A discussion of emerging themes document with the community

Report Preparation

June 11, 2021 — LRP draft recommendations presented for feedback (CAP Congress)

August 3, 2021 — draft report v1 released for community feedback

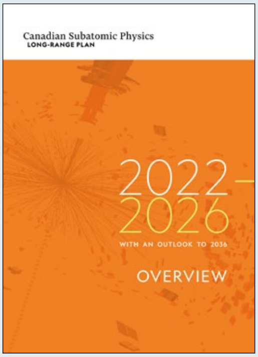
September 10, 2021 — draft report v2 released for community feedback

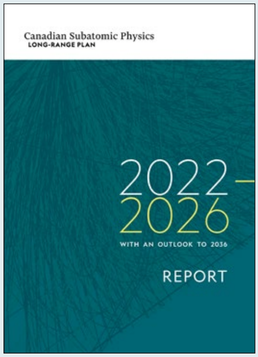
September 30, 2021 — LRP report text finalized

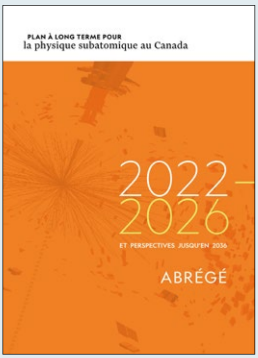
March 2022 — formatted report completed in English and French.

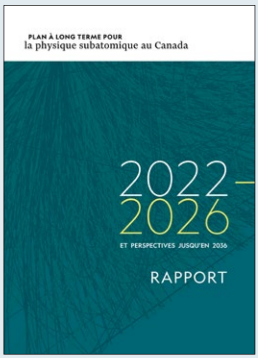
THIS PAGE: Undergraduate student Aditya Babu (Waterloo) working on the measurement of the lifetimes of short-lived nuclei using the GRIFFIN detector at TRIUMF. [Credit: TRIUMF]

"Michael Faraday didn't have a university education — he just followed his curiosity and went on to become one of the most widely regarded experimentalists in physics and beyond. Although physics research is much more specialized today, the work done at TRIUMF is considerably more collaborative and has so many more interdisciplinary applications than I ever imagined. There are people from all over the world working together, each with their own unique background. Even though almost every experiment nowadays is highly specialized in one particular field, you still need people with a diverse set of skills for it to be successful."









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Long-Range Planning Committee, "Canadian Subatomic Physics Long-Range Plan 2022–2026: Report", 2022, Canada, https://subatomicphysics.ca

This report is available as a PDF file and as native website text. An overview is also available as a PDF file.

Ce rapport est egalement disponible en français.

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Canadian Subatomic Physics
LONG RANGE PLAN

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