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IPP Submission to the NSERC Subatomic Physics Long Range Planning Committee

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IPP LRP Brief Preparatory Group*

Executive Summary:

The Canadian particle physics community has continued to grow in numbers and scientific output over the last five years and is making substantial, internationally recognised, contributions in several areas. We review significant accomplishments of Canadian researchers, and offer a vision of the priorities for the community for the next five years. We identify four "essential" projects for the particle physics community in Canada over the next five years: ATLAS, DEAP, SNO+, and T2K. We identify four additional projects that have the potential to achieve essential status within the Canadian community over this time period: EXO, PICASSO, SuperB, and SuperCDMS. A long-term solution for funding SNOLAB operations outside the NSERC SAP envelope is identified as the most critical structural issue for Canadian particle physics. We draw attention to the failure of the SAP envelope to grow in proportion to the growth of the community, funding limitations on TRIUMF's ability to support new particle physics initiatives, and exploring a formal relationship between Canada and CERN. The IPP welcomes improved coordination between the different funding mechanisms available to particle physics researchers in Canada. This would be an important first step to addressing many of the structural issues discussed here.

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1 Introduction

In the spring of 2010 the IPP was asked by NSERC, and the Subatomic Physics Long Range Planning Committee (LRPC), to prepare a brief that outlines the Canadian particle physics community's plans over the coming decade. It should also highlight recent Canadian successes, encapsulate the strengths and weaknesses of our community, and provide evidence for our impact in this international field. What follows is the requested brief.

The intended audience for this document is the members of the long range planning committee and the Canadian subatomic physics community. As we are aiming it at a specialist audience it was felt that it was not incumbent on us to include an extended review of the Standard Model and the experimental facilities we use at home and abroad. Instead we chose to focus on the science we see being addressed in the coming decade and the opportunities for particle physics research in Canada.

The brief is structured in seven sections. Section 2 provides an overview of the scientific questions the Canadian particle physics community is addressing, and expects to address, over the coming decade. Section 3 gives an overview of the accomplishments of the Canadian particle physics community over the past five years, including the training of personnel and our standing in international collaborations. Section 4 details the science objectives and how we are addressing them with our projects. Sections 5 describes the size, scope and health of the Canadian particle physics community and Section 6 highlights the structural (funding, demographic and institutional) challenges faced by our community. Section 7 presents the experimental priorities of the Canadian particle physics community. The brief concludes with a section describing examples of areas of opportunity where new funding would have a disproportionate impact (Section 8).

2 The "Big Questions" in particle physics

The Standard Model of particle physics provides an excellent description of almost all data. However, there are holes of two kinds in our understanding: phenomena not accounted for by the Standard Model (e.g., dark matter, gravity), and unnatural-seeming descriptions of phenomena for which we lack a deep understanding (e.g., electroweak symmetry breaking, flavour physics). In what follows we describe the major open questions in particle physics and briefly look ahead to how Canadian physicists are addressing them.

2.1 Electroweak symmetry breaking

The Standard Model description of electroweak interactions as an SU(2)×U(1) gauge theory has been extremely successful. Measurements at LEP experiments during the 1990s (including Canadian participation on the OPAL experiment) confirmed the gauge theory picture at the level of one-loop electroweak radiative corrections. However, the electroweak symmetry by itself forbids masses for the $W^{\pm}$ and Z bosons, and the left-handed nature of the SU(2) coupling to fermions also forbids masses for the Standard Model fermions. The success of the gauge theory picture can be made consistent with particle masses by breaking the gauge symmetry spontaneously via the Higgs mechanism. The Standard Model incorporates the simplest possible implementation of the Higgs mechanism through inclusion of a single SU(2)-doublet Lorentz-scalar field, the so-called Higgs field. Despite the extremely rigorous testing of the gauge sector at LEP, the electroweak symmetry breaking mechanism has not yet been confirmed experimentally. On the other hand, we know that the Higgs boson, or whatever replaces it, must appear below the TeV scale in order to unitarise longitudinal W and Z boson scattering. Testing the Higgs mechanism—or more generally, experimentally determining the dynamics of electroweak symmetry breaking—is therefore the primary goal of the LHC, which was built to unveil this energy range.

Testing the Higgs mechanism means determining whether the Higgs boson is the excitation of the field that gives mass to Standard Model fermions and bosons. This means measuring the couplings of the Higgs boson to fermions, W, and Z bosons, and measuring the coupling of the Higgs boson to itself in order to determine the shape of the Higgs potential and test the spontaneous breaking mechanism. The LHC will be able to measure combinations of some Higgs couplings that appear in Higgs production and decay. Extracting the individual couplings requires combining multiple measurements with model-based assumptions. A high-energy e^+e^- collider like the ILC would allow model-independent, higher-precision measurements of more couplings, including the Higgs self-coupling.

The Higgs mechanism in the Standard Model has another problem, which is that the energy scale associated with electroweak symmetry breaking—and thus the mass of the Higgs itself and all Standard Model particles that get their mass from the Higgs—is extremely unstable to radiative corrections. The usual picture of renormalisation in which the physical mass is the sum of a “bare” high-scale mass and radiative corrections requires cancellations of up to 30 decimal places if the high scale is of order the Planck scale. This is called the hierarchy problem, and it has motivated the construction of most models of physics beyond the Standard Model. In order to avoid a fine-tuned cancellation, new physics that stabilises the electroweak scale has to appear around the TeV scale. Possibilities for this new physics include supersymmetry, strong dynamics that produce a Higgs-like state as a bound state of fermions, or extra dimensions that lower the effective scale of quantum gravity to the TeV scale. All of these can be probed at the LHC, with precision measurements possible at the ILC depending on the mass scale of the new physics.

A tantalising feature of many of these fixes for the hierarchy problem is that they offer a candidate dark matter particle. Many of these models have a discrete symmetry, under which some or all of the new particles are charged, introduced to fix other problems of the model like rapid proton decay (R-parity in supersymmetry) or too-large contributions to electroweak precision observables (T-parity in little Higgs models). If this symmetry is exact, the lightest particle charged under the symmetry will be stable and can be a dark matter candidate.

The argument for new physics at the TeV scale to solve the hierarchy problem is theoretical, not based on any observations. Nature could be perverse and simply fine-tune a 30-orders-of-magnitude cancellation to give us a weak scale so much lower than the Planck scale. This possibility is suggested as a result of our failure to find an explanation for the scale of dark energy, which is apparently far more fine tuned than the weak scale, leading to appeals to anthropic selection out of vast numbers of universes that might be produced in inflation. Thus, even the absence of a solution to the hierarchy problem may shed surprising light on the deep structure of nature.

2.2 Dark matter

Over the last two decades a consistent cosmological model of the constituents of the Universe has evolved. This model is derived from a broad range of astronomical and cosmological observations, ranging between cosmic microwave background anisotropies, supernova standard-candle brightness at high redshifts, determination of nucleosynthesis abundances in the early Universe and dynamical studies of structures on all scales in the cosmos. The standard cosmological model that has evolved shows the Universe comprises

73% dark ‘energy’, 23% non-baryonic dark matter, and 4% baryons. The nature of the non-baryonic component of the Universe is still not determined, and the resolution of this question would have significant consequences for astronomy, astroparticle and particle physics. The displacement of the matter density (measured using gravitational lensing) from the bulk of the baryon density in hot gas (measured using X-ray emissions) in colliding galaxies provides strong evidence that the dark matter is particulate in nature rather than being accounted for by a modification of gravity. The Standard Model of particle physics contains no candidate particle that could account for the dark matter, providing the best evidence we have for new particle physics. The favoured solution for the non-baryonic dark matter is a new type of sub-atomic particle, beyond the Standard Model of particle physics, which would need to be stable on cosmological timescales. Such a particle would tie together extensions beyond the standard particle physics model with the dynamical behaviour of the Universe as a whole.

There are several hypothesised particles which would make ideal candidates for the non-baryonic dark matter component of the Universe. One class of these particles that is highly compelling is the Weakly Interacting Massive Particle (WIMP), which could have been produced during the very early Universe and would still be present today. A WIMP, so-called due its mass and interaction nature, is a generic class of particles produced in the hot early Universe, which would freeze out of thermal equilibrium as the Universe cooled and they became non-relativistic. One of the compelling aspects of this class of particle is that their density today is controlled by their annihilation rate during the early phase of the Universe, and assuming this annihilation cross-section is typical of the electroweak interaction, the currently observed relic density of $\sim 25\%$ is obtained. Many specific candidate particles which could be WIMPs have been studied, one of the most well-motivated being the lightest supersymmetric particle (LSP) which arises from supersymmetric extensions to the Standard Model. These extensions are predicated on solving the gauge hierarchy problem in the Standard Model, namely why the Higgs mass is not the Planck mass, and the unification of the coupling constants at high energies, rather than the solution of the dark matter problem. The LSP, typically the neutralino, would make an ideal dark matter candidate, being stable, neutral and massive.

Searches for non-baryonic dark matter particles are being pursued with three different approaches. Direct production of supersymmetric particles may be possible in high energy colliders, such as the LHC and ILC, and so searches are underway for these channels within ATLAS. Although this would demonstrate the existence of physics beyond the Standard Model, it would not demonstrate the cosmological nature and stability of these particles.

Dark matter particles should also be streaming through the solar system as we orbit the galactic centre. If the dark matter interacts through the weak interaction, it should infrequently scatter off normal matter, in particular atomic nuclei. This offers the possibility of direct detection of the ambient dark matter through measurements of the nuclear recoils. Observation of a signal would provide a rough mass measurement and a cross-section measurement in either the spin-independent or spin-dependent channel depending on the target nucleus, providing valuable information about the dark matter particle. This would be a rare, low-energy process, requiring detectors very low in radioactive backgrounds and a deep underground facility like SNOLAB free from cosmic-ray backgrounds. Existing detectors use either ionisation and phonon signals in a low-temperature semiconductor (CDMS), scintillation and ionisation in a noble liquid (DEAP, or non-Canadian experiments such as Xenon-10), or bubble formation in a super-heated fluid (PICASSO, or its US competitor COUPP).

Additionally, indirect searches for dark matter particle annihilation in gravitational traps, either the Galactic centre, the Sun or Earth, are undertaken with gamma-ray or high energy neutrino observatories such as VERITAS or IceCube.

Results from these different techniques are already beginning to constrain the types of supersymmetric model that may exist, with WIMP-nuclear scattering cross-sections approaching $\sim 10^{-44}$ cm^2 already being probed, with anticipated improvements of two orders of magnitude in sensitivity capable of ruling out a substantial fraction of the currently envisaged models.

2.3 Flavour structure of quarks

The Standard Model describes quark masses as arising from couplings of left- and right-handed quarks to the Higgs doublet through two general complex 3×3 matrices of Yukawa couplings, one each for the up-type and down-type quarks (the masses of charged leptons are incorporated in a similar way). This description allows a parameterisation for the quark masses and the CKM matrix with a single CP-violating phase, and is consistent with all flavour physics data (with the exception of a few low-significance "hints"). However, the Standard Model provides no explanation for the sizes of the Yukawa couplings, which vary by almost 5 orders of magnitude between the up quark and the top quark, nor does it explain the pattern of quark hypercharges or why there are 3 fermion generations.

Flavour physics is fertile ground for indirect new physics searches. Flavour Changing Neutral Currents (FCNC), neutral meson-antimeson mixing and CP violation occur only at the loop level in the SM and are sensitive to new physics from first order virtual corrections. Flavour physics has the potential to explore the new physics scale up to the 100 TeV region. If the new physics scale is indeed close to 1 TeV, then the flavour structure is non-trivial and the experimental determination of the flavour-violating couplings is particularly interesting. The critical role of precision-frontier physics is reflected in the substantial engagement of the international community in the LHCb experiment and its strong support for a high-intensity e^+e^- flavour factory.

Flavour physics is an important part of the scientific program of the general purpose detectors such as ATLAS, or non-Canadian experiments like LHCb or CMS. B-meson measurements at the flavour factories PEP-II/BaBar and KEK-B/Belle, accelerator experiments at the Tevatron and LHC, charm physics at CLEO, and rare kaon and pion decay measurements have provided significant constraints on the flavour sectors of possible extensions of the Standard Model. The proposed super flavour factories, SuperB and the KEK-B/Belle upgrade, would provide $\sim$100 times the existing statistics, allowing detection of effects of the size expected in, e.g., TeV-scale supersymmetry with "minimal" flavour structure. The study of flavour physics can also be done at other facilities such as the Large Hadron Collider at CERN. The large b-quark production cross-section at the LHC will allow sensitive tests of possible new physics contributions. Further, the higher energy of the LHC will result in measurements that complement those obtained at the B factories. The next generation of extremely-high-statistics kaon and pion decay experiments would also be sensitive to new physics in this energy range.

2.4 Flavour structure of neutrinos

The nonzero masses of neutrinos came as a surprise. The first hint was the deficit of neutrinos coming from the sun. Concrete evidence came in 1998 with the measurement at Super-Kamiokande of the flux difference between upward-going and downward-going muon neutrinos produced in the atmosphere by cosmic rays. The solution of the solar neutrino problem came in the early 2000s from the Sudbury Neutrino Observatory's (SNO) measurement of the total flux of electron-, muon-, and tau-type neutrinos from the sun. Higher-precision measurements of the neutrino mass-squared differences (which control neutrino oscillations) and the mixing angles between the neutrino mass eigenstates and flavour eigenstates (encoded as the PMNS matrix, the lepton-sector analogue of the CKM matrix) have been made by long baseline neutrino experiments such as K2K (with Canadian participation), NuMI/MINOS and KamLAND using neutrinos produced in proton accelerators and nuclear reactors.

The current unknowns in neutrino measurements are as follows. First, the mass ordering of two of the neutrino mass eigenstates is known but the relative mass of the third is not; the two possibilities are called the "normal" and "inverted" hierarchies. This could be determined by detection of the shift of the effective mass difference through the matter effects resulting from neutrinos traveling a long distance through the earth before detection, which is one of the major goals of long-baseline experiments. Second, there is currently only an upper bound on the amount of electron neutrino in the third neutrino mass eigenstate, parameterised by the mixing angle θ_{13}. Detection of a nonzero θ_{13} is the goal of short-baseline reactor neutrino experiments outside Canada like CHOOZ and Daya Bay and the long-baseline experiment T2K. Third, the CP-violating phase in the PMNS matrix has not been measured. This could be revealed by comparing the oscillations of neutrinos and anti-neutrinos at T2K if θ_{13} is not too small. Finally, while the differences in the squares of the neutrino masses are known, their overall mass scale is not. This is constrained and will be further probed by measurements of the electron kinematic endpoint in beta decay of tritium. If the neutrino is a Majorana particle, it will also be probed by neutrinoless double beta decay experiments discussed below.

Incorporating neutrino masses into the Standard Model requires new physics. The simplest possibility is to implement neutrino masses through a Higgs coupling in the same way as other fermion masses. This requires introduction of a sterile (non-interacting) right-handed neutrino state for each of the three left-handed neutrinos, with dimensionless Yukawa couplings of order 10^{-11}. Because these right-handed neutrinos are completely neutral under the Standard Model gauge interactions, gauge invariance does not forbid a Majorana mass term for the right-handed neutrino, with a mass scale unrelated to the electroweak scale. A sufficiently large (order 10^{14} GeV) Majorana mass for the right-handed neutrino leads to a naturally light left-handed Majorana neutrino without need for extremely tiny Yukawa couplings. The question then arises, what physics is responsible for the large Majorana mass and the flavour structure in the lepton sector?

A variety of lower-energy models for neutrino masses have been introduced, many with additional new physics at the electroweak scale, such as right-handed Majorana neutrinos or additional Higgs fields with significant couplings to neutrinos. These are testable through new-particle searches at the LHC, as well as searches for flavour violation in the lepton sector such as $\mu \to e\gamma$. The ultimate explanation of the structure of lepton masses and the PMNS matrix faces the same problems as in the quark sector.

Addressing the question of whether neutrinos are Majorana or Dirac particles requires the search for lepton-number violating processes. In some models this can be done at the LHC, but the best bet is the direct search for lepton number violation through neutrinoless double beta decay. Observation of neutrinoless double beta decay would also provide a measurement of the absolute mass scale of neutrinos, because the rate is proportional to the square of an effective electron neutrino Majorana mass. Detection of neutrinoless double beta decay requires a large quantity of a suitable isotope in a very low background environment, with a way to measure the energy of the two decay electrons in order to distinguish the neutrinoless decay from ordinary two-neutrino double beta decay. Current Canadian efforts are SNO+ using ^{150}Nd and EXO using ^{136}Xe.

2.5 Reaching to higher energies: gravity, symmetry and the quest for unification

The Standard Model provides a very good "effective theory" of physics at and below electroweak-scale energies. It leaves unanswered questions about the physics at higher energy scales. For example, the Standard Model fails to provide a working explanation for the excess of matter over antimatter in the universe. Extensions of the Standard Model may account for this through electroweak baryogenesis; alternatively, high-energy-scale physics responsible for Majorana neutrino masses may also lead to the matter-antimatter asymmetry through "leptogenesis." Grand unification of the strong, weak, and electromagnetic forces would provide new sources of baryon number violation, testable through searches for proton decay or neutron-antineutron oscillation, as well as explaining the unusual pattern of hypercharges of the quarks and leptons. Grand-unified theories can also incorporate magnetic monopoles, which may be producible in colliders if their masses are low enough.

Ultra-high-precision searches for violation of Standard Model symmetries and deviations from expected force laws extend our knowledge of the validity of physical principles. A positive signal in such an experiment would revolutionise our understanding of nature.

2.6 High-energy particle astrophysics

One research area on the boundary between particle physics and astrophysics that has been traditionally supported from the subatomic physics envelope is high-energy particle astrophysics. This field includes the detection and study of high-energy particle emissions, especially gamma-rays and neutrinos, from astrophysical objects such as active galactic nuclei, pulsars, and supernova remnants. High-energy neutrinos and gamma-rays are produced when charged particles are accelerated to ultra-relativistic speeds in the extreme astrophysical environments, such as in the jets of an active galactic nucleus, which are believed to be ultimately powered by accretion of matter onto a central supermassive black hole. Observations of gamma-rays or neutrinos from such sources can shed light on the mechanisms that power these sources. While many of the questions being addressed here are astrophysical in nature, the experimental techniques used come from particle physics, and many scientists trained in this area move seamlessly from particle astrophysics to more traditional particle physics experiments. High-energy particle astrophysics can also directly address certain questions in particle physics. For example, annihilation of heavy dark matter candidates in space may produce an annihilation signature in either gamma-rays or neutrinos that could provide the first detection of dark matter particles, in a way that is complementary to terrestrial searches such as those described in Section 4.4.

2.7 Dark energy

Undoubtedly the most surprising result in cosmology of the last 15 years, and possibly the biggest surprise in all of physics and astronomy, is the discovery that the universe's energy budget is dominated by a smooth energy component of unknown origin with an effective negative pressure. This component, known as "dark energy", is responsible for the accelerating expansion of the universe, and measurements of this expansion from observations of Type-Ia supernova at high redshifts provide some of the best constraints on the magnitude and origin of dark energy.

Although the nature of dark energy is mysterious, it is widely believed that any explanation must come from particle physics. Although a small, non-zero cosmological constant provides the simplest solution to the origin of dark energy, our current knowledge of particle physics predicts the wrong size for such a cosmological constant by ~ 100 orders of magnitude—a failure of theory of catastrophic proportions. It is highly likely that any explanation of dark energy, whether as a cosmological constant or in models which allow the dark energy to have alternative time evolutions, will ultimately invoke new fields and mechanisms beyond the Standard Model. The current accelerated expansion is reminiscent of the much faster inflation that is believed to have occurred immediately after the Big Bang and accounts for the extreme smoothness and uniformity across parts of the universe that have been causally disconnected since then. Better measurements of the cosmic microwave background and the accelerated expansion may provide hints into these problems. Short-distance tests of gravity like modern versions of the Cavendish experiment and measurement of quantum states of ultra-cold neutrons in the gravitational potential may shed light on extra-dimensional possibilities.

Explorations of dark energy have attracted significant interest from particle physicists worldwide. Outside Canada a number of particle physicists are contributing to proposed missions such as WFIRST or LSST that seek to measure the astronomical effects of dark energy. In some cases they contribute through their experience in handling petabyte-scale data sets or in organising large international collaborations. In others experimental techniques from particle physics can be more directly appropriated.

3 Accomplishments of the Canadian particle physics community

At the time of the last LRP report, the Canadian particle physics community was actively engaged in the collection and analysis of data from the BABAR experiment at SLAC, the CDF and D0 experiments at FNAL, the SNO experiment and ZEUS at DESY, as well as a host of smaller projects. In addition, construction and installation of the ATLAS detector at CERN was well underway. In the past five years,the situation has changed dramatically and the accomplishments of the Canadian community have been remarkable.

Data taking at the Canadian-based Sudbury Neutrino Observatory (SNO) ended in November 2006, following the third phase of operations in which 40 newly installed ^{3}He gas filled counters were used to enable a systematically independent check of previous SNO results. These measurements, summarised in Figure 1, allowed SNO to confirm its previous observations of the solar neutrino flux, while aggressive improvements in the analysis allowed SNO to reanalyse previous data at a much lower energy threshold, with a factor of two reduction in most major systematics. The heavy water was returned to AECL and OPG by December 2007, marking the successful culmination of the SNO operational program. The SNO detector remains in the Creighton mine and is being given a new life as part of the SNO+ project in the new SNOLAB facility. The highly successful SNO project conclusively demonstrated that solar neutrinos oscillate on their way from the core of the sun to the earth, thus resolving the long standing solar neutrino problem and proving that neutrinos have mass. Over 80 Canadian theses (PhD's or MSc's) have resulted from this work. In the past decade, the core publications of the SNO collaboration have generated more that 4500 citations. This has been accomplished under the leadership of Arthur McDonald (Queens). Art is the recipient of several highly visible awards (including the 2010 Killam prize and the 2007 Benjamin Franklin Medal in Physics) and has achieved a position of great respect and credibility in the scientific community. As the Director of SNO, and the SNO Institute, he and his team have made Canada world leaders in the field of astroparticle physics. With SNOLAB now operational, the facility has caught the attention of researchers world wide, and a very strong experimental program of world class experiments is now underway.

PICASSO is a Canadian-led and largely Canadian funded search for dark matter that has reinvented

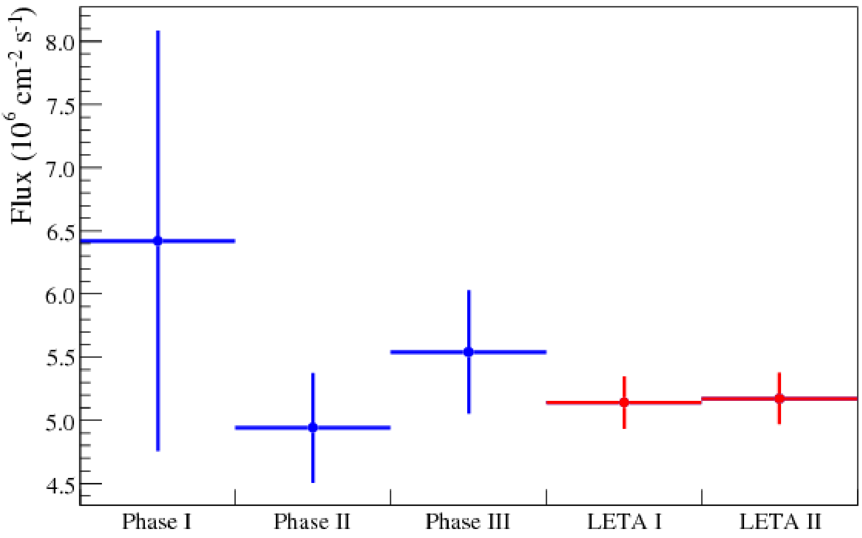

Figure 1: The SNO experiment's determination of the ^{8}B solar neutrino flux from each of their three phases of running. The two points on the right show the results of a combined Low Energy Threshold Analysis (LETA) of SNO's Phase I and Phase II data, with dramatically reduced systematics. The sharp reduction in uncertainties on the NC flux has placed tight constraints on the neutrino mixing angle θ_{12}.

the use of super-heated liquid detector technology (ie. bubble chambers). The experiment PICASSO has been very successful in attracting students. Twenty MSc and PhD theses have been completed based on the construction and physics results from PICASSO. The analysis of a first set of two out of 32 new-generation detectors totaling 14 kg·d exposure resulted in the world best limits on spin dependent WIMP interactions. By comparison, the exposure of competitors is at the level of hundreds of kg·d. For a neutralino mass of M_{WIMP} = 24 GeV/c^2 an upper bound on the spin dependent cross section on protons was found of $\sigma_p = 0.16$ pb at the 90% C.L. This result published in Physics Letters B in November 2009 rules out a substantial part of the allowed parameter space of the DAMA/LIBRA experiment. The analysis is presently being extended to the remaining 30 detectors that have been operated in 2009/10. A very competitive limit will be obtained soon. PICASSO also observed a significant difference between the maximum amplitude and signal energies in the acoustic wave forms induced by neutrons and alpha particles in their detectors. This effect allows discrimination on an event by even basis. It has the potential to substantially improve the background suppression in PICASSO and in other dark matter experiments based on super-heated liquids like COUPP, who have equipped their detector with acoustic sensors and were able to confirm this effect.

The ZEUS/Canada group has actively participated in ZEUS experimental operations and data analysis since 1991. Over the years, a total of 14 faculty members and 29 research associates have contributed to this effort, and a total of 29 Canadian Ph.D. theses and 9 M.Sc. theses have been granted. Substantial Canadian contributions to ZEUS were enabled by a strong presence at DESY, including significant hardware and operational responsibilities for calorimeters and the straw tube tracking system. Canada has contributed leadership in the form of a ZEUS physics coordinator (J. Martin, IPP-Toronto). Since the last LRP, three Canadian institutions (Toronto, McGill, York) have continued their participation in

ZEUS. The physics program has shown great breadth and impact, with over 180 physics publications to date. Proton structure function measurements, which are of particular importance for the LHC physics program, and measurements utilising the forward neutron calorimeter in particular have benefited greatly from Canadian contributions. The HERA *e*-*p* collider successfully ended its operations in June 2007. As a unique experimental facility, the measurements performed by ZEUS represent an important scientific contribution.

Canadians have been instrumental in many of the important physics results to emerge from the Tevatron in recent years. Canadian groups (Alberta, McGill, Simon Fraser, Toronto, TRIUMF and York) have actively contributed to both the CDF and $D0$ experiments, participating in the first observation and subsequent measurement of single top quark production and of B_s mixing, precise determinations of the W boson mass, and searches for the Standard Model Higgs boson. The single top measurement provided the first direct measurement of the weak interaction coupling of the heaviest known fundamental particle to a W boson, determining the Standard Model CKM matrix parameter $|V_{tb}|$ and constraining possible contributions from new physics at high mass scales. Both the Canadian CDF and $D0$ groups played separate leading roles in the single top observation. D. O'Neil (Simon Fraser) presented the first public announcement of the $D0$ discovery in a FNAL seminar in 2006, while B. Stelzer (Simon Fraser), who lead the CDF single-top effort, presented the combined Tevatron single-top discovery in 2009. At about the same time, the CDF and $D0$ collaboration announced the observation and precise measurement of the B_s^0 meson mixing frequency, a key flavour physics measurement which had eluded experimental searches for three decades and which was one of the principal targets for the LHCb experiment at CERN. The first $D0$ B_s limit publication, which included significant contributions from the Canadian group while the subsequent precision measurement of the B_s mixing rate, by CDF, relied on the precise mechanical alignment of the inner silicon tracking layers made possible by an NSERC-funded contributions to the CDF-II upgrade, and was the most highly cited experimental particle physics paper in 2006. Members of the Canadian CDF group led the precise CDF W boson and top quark mass measurements (shown in Figure 2), observables that provide the most precise indirect constraints on the mass of the Higgs boson today. Canadian CDF groups have also contributed significantly to the Tevatron Higgs search, in particular the golden associated WH production mode.

Canadian participation in the BABAR experiment has remained strong since the time of the last LRP, with participation from four institutions (McGill, UBC, Montréal, Victoria). The success of the BABAR experimental program was recognised by the Nobel committee in 2008, with the awarding of half of the physics prize to Kobayashi and Maskawa following the experimental confirmation by the SLAC and KEK B-factories of their explanation of the mechanism for CP violation within the Standard Model. This validation of the Kobayashi-Maskawa mechanism was partly the result of precise measurements by BABAR of CKM matrix parameters in a variety of related but independent B meson decay modes. BABAR's extremely rich physics program has to-date resulted in the publication of over 450 physics papers, with a sustained publication rate since 2005 which exceeds that of all other HEP experiments. The Canadian hardware operational effort, which was centered around the large volume drift chamber constructed at TRIUMF, came to successful close with the the end of BABAR data-taking in 2008. A strong Canadian presence in the collaboration has continued, with key contributions and leadership by Canadians in many of the most active areas of physics analysis. BABAR Canada members are recognised world leaders in the areas of semileptonic and rare B decays, quarkonium and exotic hadron spectroscopy, and tau lepton physics. Substantial Canadian leadership within this project is evident, with the positions of BABAR spokesperson (M. Roney, UVic) and physics coordinator (S. Robertson IPP-McGill) both currently held by members of the Canadian group, and C. Hearty (IPP-UBC) and Roney both previously serving terms

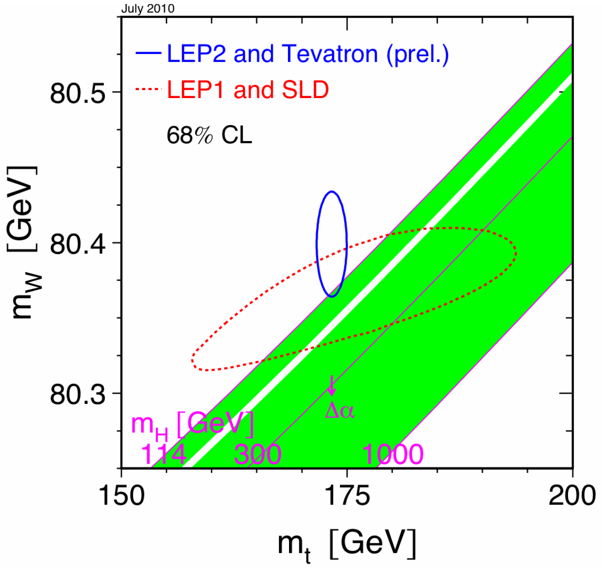

Figure 2: Measurements of the *W* boson and top quark masses that are now dominated by CDF and D0 measurements with strong Canadian involvement. Within the context of the Standard Model these provide constraints on possible Higgs masses.

as physics coordinator.

Since 2005 a large group of Canadians has made major contributions to the T2K experiment, which began operation in early 2010. Canada is one of the largest groups in T2K, with almost 30 PhD investigators – more than 10% of the collaboration. Canadian groups are responsible for the tracker, consisting of fine-grained scintillating detectors and large-volume time projection chambers, for T2K's near detector, and an optical transition radiation (OTR) beam monitor for the primary proton beam. R& D activities for these detector components was in its early stages at the time of the last LRP exercise. Since then these detectors were funded from the NSERC SAP envelope, designed and constructed, and tested in TRIUMF's M11 beamline. They have been subsequently installed and commissioned in 2009, and T2K completed its first data run in 2010. The TRIUMF laboratory hosts the largest T2K analysis centre in the collaboration. The Canadian group is playing the critical role in T2K's analysis effort with H. Tanaka (IPP-UBC) currently serving as near detector physics coordinator and A. Konaka (TRIUMF) co-convening the T2K-SK data analysis group. Canada has the largest number of people in analysis leadership positions of any country within T2K, other than the host country Japan.

Canadian involvement in ATLAS has continued to increase as interest and anticipation of LHC physics results has grown, and Canada's faculty-level commitment to ATLAS has nearly doubled since the last LRP exercise; by rough estimates, nearly $100M has been committed by Canada to ATLAS and the LHC accelerator complex over the past fifteen years. Over 130 Canadians are authors on ATLAS publications and almost 100 students and postdocs are active participants. ATLAS-Canada has successfully delivered on its major hardware construction and commissioning projects, including the hadronic endcap and forward calorimeters and electronics, as well as aspects of the high level trigger system and beam conditions, luminosity and radiation monitoring. In the first period of data taking the Canadian forward and hadronic endcap calorimeters have operated according to design expectations and with near-perfect operational efficiency. Canadians are playing critical roles in detector calibration and monitoring of ATLAS Data Quality

(McPherson, IPP-Victoria) for physics extraction. R. Teuscher (IPP-Toronto) is currently co-convener of the ATLAS Jet-Etmiss group. The Tier-1 ATLAS computing centre at TRIUMF was successfully commissioned and is currently fully operational, hosting primary and derived data and ATLAS simulation. It regularly ranks among the top in the world delivering 99% availability for 24/7 operation during ATLAS data-taking. M. Vetterli (Simon Fraser) is currently the chair of the LHC Grid computing collaboration board.

A first ATLAS physics paper was published on charged particle multiplicities in 900 GeV data was published in early 2010 and first 7 TeV physics results were presented with much fanfare at the ICHEP 2010 conference, including not only physics validation and Standard Model measurements, but also the first results of exotic searches with sensitivity exceeding that of the Tevatron. P. Savard (TRIUMF-Toronto) is currently co-leader of the ATLAS Exotics physics group. These new results usher in an exciting and much anticipated new era of physics exploration at the LHC, and Canadians were the lead analysts and authors in this effort. Canadians have contributed not only to the data analyses and authors of the ATLAS PRL on these new results, but also to the specific data calibration and reconstruction efforts that make these seminal results possible. This effort is being recognised within ATLAS by the selection of Canadians for prestigious talks and coordination roles. ATLAS Canada faculty, students and postdocs are actively engaged in many other leading-edge analysis efforts covering the spectrum from standard model measurements to the search for the Higgs boson, Supersymmetry and other exotica.

The Canadian theory community has expanded since the last LRP to encompass over 70 faculty members working in particle theory at Canadian institutions, as well as approximately 150 postdocs and graduate students. Seventeen new faculty have been hired at Canadian institutions since 2005, roughly equally split between phenomenology and more formal theory topics. The expanding role of the Perimeter Institute (PI) within the Canadian theory scene has also become apparent since the last LRP, with 11 grant-eligible researchers and about one third of all theory postdoc positions in Canada being associated with PI. Progress has been made in the coupling between theory and experimental groups, in particular the prospect of new energy-frontier physics from the LHC has motivated a number of joint theory-experiment workshops with ATLAS Canada over the past few years.

4 Achieving our scientific goals: an introduction to the Canadian particle physics program

The main objective of the particle physics community in the coming decade will be the search for new physics beyond the SM. ATLAS and the LHC experiments have started recording data and are searching for signals of new physics. The community will also be probing the neutrino sector at SNOLAB in Sudbury and T2K in Japan, while direct dark matter searches look for evidence of new particles beyond the Standard Model.

In this section we review current and proposed programmes in particle physics within the Canadian program, and discuss how they help to achieve the scientific goals outlined in Section 2.

4.1 Electroweak symmetry breaking

The mechanism for the breaking of the electroweak symmetry and how the fundamental particles acquire mass is still unknown, and discovering it is one of the major research priorities of the field. The field has chosen to follow the two-step approach that worked well with the initial discovery of the symmetry: a hadron machine to discover the mechanism followed by an electron machine to perform precision measurements of the physics. Canadian physicists are playing leading roles in both steps of this approach with a large, diverse group working on the ATLAS experiment at CERN and a strong involvement in the planning and design of the future International Linear Collider (ILC) project. Implicit to the success of any energy frontier physics program is the availability of cutting-edge particle accelerators. With efforts based at TRIUMF but supported by a number of universities, Canadian researchers are developing accelerator R&D capabilities that will allow us to contribute to the next generation of colliders as well as to their associated experiments.

4.1.1 The ATLAS experiment

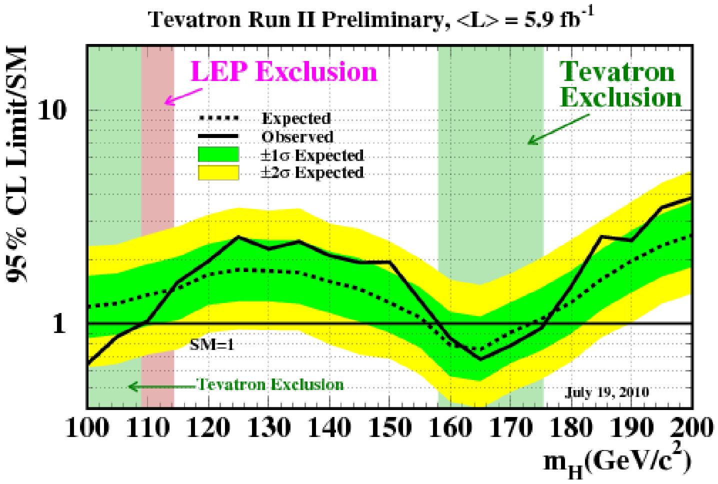

Figure 3: Plot from the Tevatron experiments showing the current experimentally excluded mass range of the Higgs boson.

ATLAS is one of the flagship experiments of the Large Hadron Collider at CERN and, as such, has received considerable media attention. It has been designed with the discovery of the electroweak symmetry breaking mechanism as one of its primary goals. The leading contender to explain this is the Higgs mechanism which, in its simplest form, has been incorporated into the Standard Model. The allowed mass range for the associated Higgs boson is from 114 GeV/c^2, from direct search by LEP, to the W-W scattering unitarity bound at 1 TeV/c^2 with a small window around 160 GeV/c^2 excluded by the Tevatron experiments (see figure 3). Since the Higgs couples to a particle's mass the predominant decay products vary considerable over this range leading to the requirement for a general purpose detector which can employ a diverse range of techniques to cover the allowed mass range.

ATLAS has a large Canadian involvement consisting of 43 faculty in 11 Canadian institutions. Ten of the new hires in experimental particle physics over the last 5 years are now fully involved in the ATLAS experiment. The group has built on the existing track record at CERN of Canadians involved in the OPAL experiment and has recently grown with the addition of many new faculty joining from the DØ and CDF experiments on the Tevatron at Fermilab. Initially the group was responsible for the construction of two wheels of the hadronic endcap calorimeter, including the cable feedthroughs and readout electronics as well as the forward calorimeter. With the recent addition of new faculty the group's involvement has expanded to include major hardware and software contributions to the ATLAS High Level Trigger, and Canadians have also been a driving force behind the design, development and deployment of the new LUCID luminosity sub-detector. Canadians have also had active roles in the ATLAS leadership with Canadians serving as Collaboration board chair, physics conveners, and Speakers committee chair, among others. The Canadian theory community has also been ramping up involvement in LHC phenomenology, with efforts underway at several institutions.

After the problems with a superconducting power bar in 2008 the LHC restarted in late 2009 at a reduced centre of mass energy of 7 TeV. The machine is currently ramping up in luminosity with peak luminosities currently around 10^{31} $\text{cm}^{-2}\text{s}^{-1}$ (as of September 2010) and ATLAS has recorded 4 pb^{-1} of integrated luminosity. The detector is performing extremely well with over 94% of data collected being tagged as good for physics with the LAr hadronic calorimeter and forward calorimeters achieving efficiencies of 98.7% and 99.3% respectively. The intent is to continue with the current run for the rest of 2010 and 2011 before stopping for approximately one year, in 2012, to make upgrades and repairs with the aim of running in 2013 and beyond at the full design energy of 14 TeV.

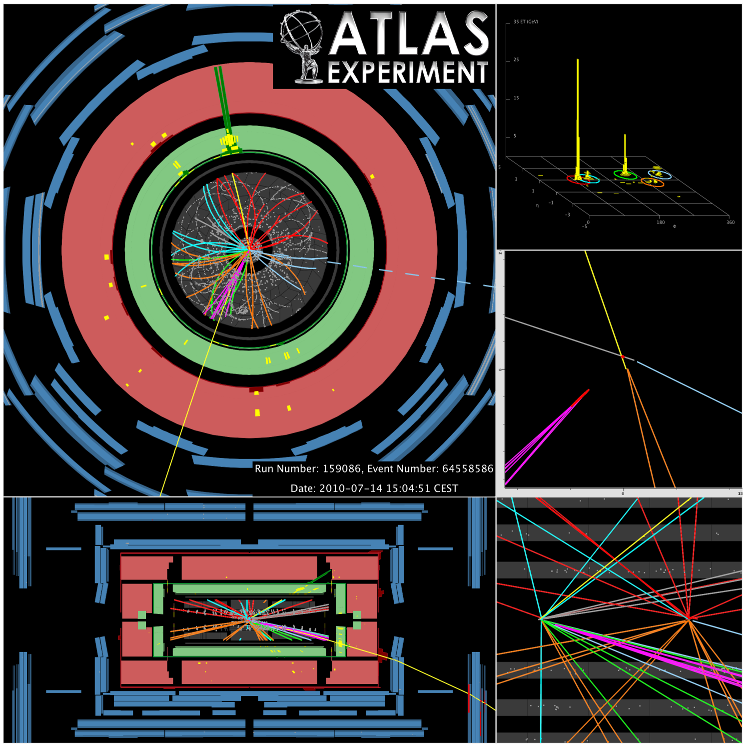

Figure 4: Electron+jets top quark candidate event. The bottom right panel shows pile-up in the form of two primary vertices with the zoomed panel above showing the displaced vertex associated with the b-jet tag.

Analysis of the existing data is going well. The three-tier GRID computing model has performed extremely well with over 1,000 users submitting GRID-based analysis jobs. Canada hosts a Tier 1 computing centre at TRIUMF and four regional Tier 2 computing centres distributed throughout the country. These have been realised using CFI funds either directly, in the case of the Tier 1, or indirectly via Compute Canada for the Tier 2's. Initial detector performance results as well as observation and measurement of known Standard Model processes (a candidate top quark event is shown in Figure 4) have already been presented. More significant results are expected for the Winter 2011 conferences.

The current ATLAS data taking period is foreseen to continue throughout the period of the next 5 year plan. However there are already upgrade plans for the LHC to increase the design luminosity by another order of magnitude in stages. In addition to this several of the detector subsystems will also be reaching their radiation damage limits by about 2014. The Canadian ATLAS group is already getting involved in the detector upgrade R&D effort in the areas of very high rate energy measuring calorimeters, advanced high rate Cherenkov counters and thin, radiation tolerant pixel radiation detectors. Future involvement may also include the trigger and DAQ upgrades. Possible Canadian contributions to ATLAS upgrades are detailed further in Section 8.3. If the physics out to $\sqrt{\hat{s}} \approx$ few TeV doesn't warrant luminosity increases CERN has already begun to explore options to upgrade the energy of the LHC to 28 TeV in proton-proton collision centre of mass. Any such effort will be well beyond the current planning period and Canadian researchers have not yet identified possible roles in this upgrade.

4.1.2 The International Linear Collider

The International Linear Collider (ILC) is a proposal for a new e^+e^- linear collider operating at a 0.5-1 TeV centre of mass energy with the stated aim of performing precision studies of the EWSB mechanism as well as possible beyond-the-SM physics coming out of the LHC data. The choice of a linear collider is dictated by the energy, since synchrotron losses due to the low mass of the electron would be excessive for any practical ring size. The project is still in a design and planning stage with Canadians playing leading roles in both the accelerator and detector research and development, as well as theoretical efforts in ILC phenomenology and coordinating roles in the world-wide studies for the physics case.

The design of the ILC calls for super-conducting radio frequency (SRF) cavities with a 35 MV/m gradient, and Canadians are developing the expertise to be able to construct such cavities here in Canada working with industry. Although the eventual aim is to use such cavities in the ILC the nearer-term goal is to use five of these cavities to construct a high intensity electron accelerator at TRIUMF for use in nuclear physics and medicine. Development of the 50 MeV eLINAC, part of ARIEL, is one of the major features of the TRIUMF 5-year plan. Tests on single cell cavities are already being carried out at TRIUMF and Fermilab, and the team plans to move towards testing Canadian-built 9-cell cavities by 2012/13. In addition to cavity testing the group is also developing novel "second sound" temperature wave sensors to improve localisation and detection of quench events on the cavity's surface. Researchers from three universities (Toronto, UBC and Victoria) are collaborating with members of the TRIUMF accelerator division to develop Canadian expertise in high-power, high-gradient SRF cavity design, production and testing. All three are working to develop graduate programs in accelerator physics to train the next generation of Canadian accelerator experts and are actively recruiting graduate students. The IPP believes this is an initiative that should be supported independent of its connection to the ILC. Advances in accelerator technology under-pin the future of experimental particle physics. Canadians should be more involved in pushing this technology if our community it to stay at the forefront of our field.

The Canadian ILC detector development effort is focused around two areas: time projection chambers (TPCs) and calorimetry. Canadian groups have been active in the ILC TPC R&D since 1999 and have made significant contributions to the field. The new TPC readout concept of charge dispersion was developed in Canada and has demonstrated the feasibility of achieving the, un-precedented, 100 μm resolution goal for the full sized ILC TPC. Charge dispersion has been adapted for further development by the international LCTPC collaboration. Since 2005 Canada has been a member of the CALICE collaboration for ILC calorimetry and has been actively involved in analysing test beam data collected at CERN in 2007 and at Fermilab in 2008.

The world-wide consensus, established in 2004, that an e^+e^- collider will be needed to make precision measurements following any LHC discoveries, is being tested. Delays to the LHC have pushed back the earliest possible time for additional experimental motivation for such a machine to 2013 or 2014. Further, if the LHC discoveries indicate that the energy needed to study new phenomena is beyond 1 TeV an alternative to the SRF technology that underpins the ILC design will be needed.

In the coming five years the focus of the ILC community will be the completion of a cost-to-performance optimisation of the accelerator and detector designs. Given suitable physics motivation, this would put the international particle physics community in a strong position to move forward quickly to propose such a large internationally cooperative project. In parallel, R&D on alternative accelerator technologies, such as CLIC or a muon collider, with the potential for higher lepton collision energies is being pursued in the event that more than 1 TeV is needed to precisely measure the new physics uncovered at the LHC.

4.2 Flavour structure of quarks

The study of the flavour structure of the quark sector has been a key area of research for Canadians. In particular, Canada's efforts over the past decade in flavour physics have centred around the BaBar experiment which ended 10-years of data-taking in 2008 and continues to analyse its data set. In addition, Canadians have a track record of being involved in the area of flavour physics with the OPAL, CDF and CLEO experiments. The primary physics goal has been the study of CP violation in the decay of B mesons, or, more generally, the study of the Unitarity Triangle that characterises the CKM description of the weak force within the Standard Model (SM). BABAR, together with Belle and other experiments, has made a wide range of measurements that over-constrain the SM. Searches for evidence of new physics have also been an important aspect of the heavy flavour physics program. Although deviations from SM could be evidence for a heavy virtual particle, the current observations are all consistent with the SM. The sum of these measurements give a consistent description of the triangle (see fig. 5).

The team of ten Canadian faculty members at four universities have made a significant contribution to the BaBar detector with the construction of the drift chamber at TRIUMF and providing computing resources for both simulation and analysis. The group is active in analysis, having generated 24 publications as primary authors, and in the training of highly-qualified personnel (currently there are 12 graduate students on the project). The Canadian group has focused its efforts on the SuperB project being proposed in Italy. A technical design report describes the physics goals, detector and accelerator for a facility that will provide a 100-fold increase in luminosity compared to that seen by previous *B* factory experiments. The proposed site is near the INFN laboratory in Frascati. Their existing international collaboration includes Canada, France, Italy, Poland, Russia, Spain, the US, and the UK. The funding decision rests with the most senior levels of the Italian government and a decision is expected in 2010. An upgrade to the Japanese *B* factory is underway. If the SuperB project is not approved, then the Canadian group will explore participation in the Super-Belle project.

The SuperB detector design has many of the characteristics of the existing BABAR detector. There are new challenges as the higher luminosity generates more backgrounds, including low-angle Bhabha and

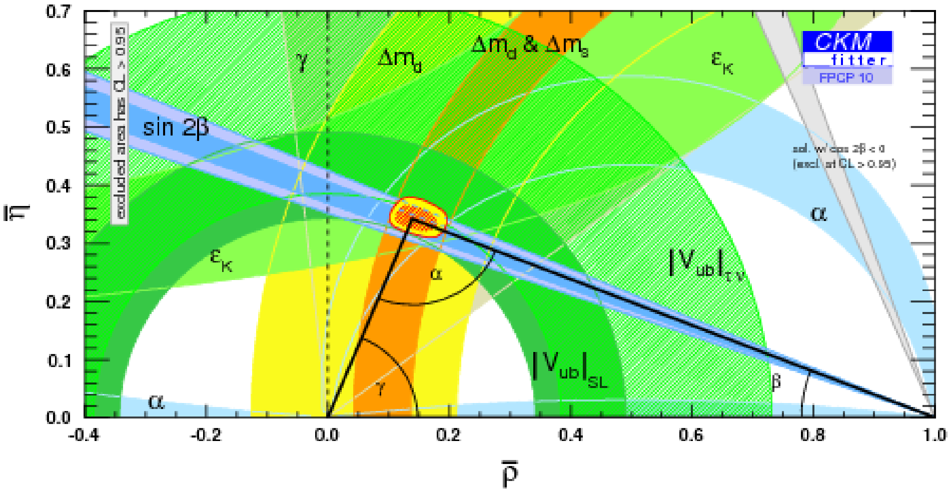

Figure 5: A fit to the latest data in the $\rho-\eta$ plane by the CKM fitter group.

two-photon events which will likely influence aspects of the detector design. Many components from the PEP-II machine and the BABAR detector can be reused in SuperB. The INFN has already issued a formal request to DOE/SLAC for the PEP-II components and there is an informal understanding that most of the useful components of both PEP-II and BABAR will be shipped to Italy.

The Canadian group includes physicists from Carleton, UBC, TRIUMF, McGill, Montreal and Victoria, with the group expected to be as large as the existing BaBar Canada group. Given its strengths, the group is focusing its detector research and development efforts on the problems of the gaseous tracking system in a high-luminosity environment. Canadian proponents have authored several sections of the project reports detailing the scientific goals. For example, $B \rightarrow X_S\gamma$ is important in new physics scenarios involving flavour violation and $B \rightarrow l\nu$ decays can be used to probe the Higgs Doublet Model. Theoretical input relevant to these studies has come from the groups at Montreal, Victoria, Alberta, and Concordia, as well as from the lattice QCD community, particularly at TRIUMF and SFU.

The SuperB design includes the possibility to polarise one of the beams. With polarised beams one has the ability to cleanly measure CP asymmetries and search for a EDM, and it also provides an incisive tool to suppress backgrounds in lepton flavour violation searches. Polarisation also opens a new window on precision neutral current measurements. The combination of high luminosity and polarised electrons at SuperB provides a unique opportunity to measure a number of electroweak neutral current parameters, such as $\sin^2\theta_W$ with a precision comparable to the current world average.

Although the main goal is the search for physics beyond the SM, ATLAS will also make measurements that are sensitive to new physics such as rare b decays with muons and/or photons in the final state, and measurements of CP violating parameters. The ATLAS b-physics program includes the new physics search, such as a measurement of the CP violating phase ϕ_2 of the B_s^0 system, searching for anomalous rates of rare B-decays, as well as precise tests of QCD by studying of the production mechanisms of $b\bar{b}$ pairs, beauty baryon polarisation, and lifetime measurement. At the design luminosity of 10^{34} cm^{-2} s^{-1} ATLAS will search for the rare B decays and measure quantities sensitive to possible new physics. High precision B physics measurements will be performed with the luminosity of 10^{33} cm^{-2} s^{-1}. The amount and type of B physics data collected by ATLAS will depend on the eventual instantaneous luminosity evolution of the LHC. In order to reduce the background from the decay of kaons and pions in flight, it is necessary to impose a p_T threshold around 5-10 GeV to keep the event rate at a manageable level. At low luminosities, the thresholds can be lowered, but as the luminosities increase the levels will be adjusted to match the capacity of the system. In the middle of this decade, ATLAS plans to install a fast vertex finding trigger system similar to the one used currently by CDF, making *b* physics more accessible at the highest luminosities.The ATLAS-Canada group includes a number of faculty with expertise in flavour physics at the Tevatron and the SLAC *B* factory. Many Canadians are already active in this physics.

4.3 Neutrino physics

The study of the flavour structure of the neutrino sector has been a highly successful area of research in Canada over the past decade. The highly publicised discovery of oscillation of solar neutrinos with the SNO experiment in 2001 was followed by precision measurements of the flavour composition of the ^{8}B flux, Δm^2_{12} and $\tan^2\theta_{12}$. Canadians played the leading role in SNO and are still very dedicated to the neutrino sector: seven of the faculty hires of the past five years had made strong contributions to SNO and continue to focus most of their research time in this field. Canadian theorists have also been active in neutrino model-building and phenomenology, as well as nuclear physics contributions needed to understand expected experimental signatures.

Five primary physics goals are identified in the neutrino sector, all of which are being aggressively pursued by Canadians. The mass ordering of the neutrino mass eigenstates (normal versus inverted hierarchy) and θ_{13}, a parameter for the amount of electron neutrino in the third mass eigenstate m_3 are both investigated by the T2K experiment. T2K could also observe the CP-violating phase in the mixing matrix if θ_{13} is not too small. The overall mass scale of neutrino masses and the Majorana or Dirac nature of neutrinos are pursued by the neutrino-less double beta decay experiments SNO+ and EXO. Observation of this process requires lepton number violation.

4.3.1 SNO+

SNO+ builds on the SNO infrastructure by replacing SNO's heavy water with liquid scintillator. By transforming SNO into a liquid scintillator detector, a new experiment with diverse physics goals was created. The detection of low-energy solar neutrinos and in particular the *pep* solar neutrinos has the potential to probe the neutrino-matter interaction with sensitivity to new neutrino physics. The detection of electron anti-neutrinos from natural radioactivity in the Earth (geo-neutrinos) will address key questions in the field of earth sciences. The detection of electron anti-neutrinos from distant nuclear power reactors (e.g. Bruce, Darlington, Pickering) can confirm previous observations of reactor neutrino oscillations. Next, a competitive, next-generation double beta decay experiment can be carried out with ^{150}Nd loaded in the liquid scintillator. Finally, the SNO+ detector maintains excellent supernova neutrino capabilities.

The SNO+ Canadian contingent consists of 14 faculty from Alberta, Laurentian, Queen's, SNOLAB and TRIUMF forming close to half of the collaboration with over 30 people, many of whom are 50% DEAP and 50% SNO+. Foreign collaborators come from Brookhaven, Dresden, Black Hills, Armstrong, Leeds, Liverpool, LIP Lisbon, UNC, Oxford, Pennsylvania, QMU London, Sussex and UW.

SNO+ has designed a low-radioactivity hold-down net for the acrylic vessel, which becomes buoyant when filled with liquid scintillator. The scintillator purification and process system has been designed by the company that provided the purification system for Borexino. The necessary excavation is underway and the system will be completed in late 2011. The initial fill will begin in November 2011, with water. The liquid scintillator will be received starting in early 2012. SNO+ is also upgrading the SNO photomultiplier DAQ system to be able sustain much higher event rates and take advantages of advances in readout electronics components that have occurred over the last fifteen years.

SNO+ will start taking data in 2012 and will run in two phases. The first phase will study double beta decay with 780 kg natural neodymium (corresponding to 44 kg ^{150}Nd) loaded at 0.1% by weight in the liquid scintillator. ^{150}Nd has a very high endpoint value at 3.4 MeV placing the $0\nu\beta\beta$ signal above most radioactive backgrounds. It also has the highest phase space factor, corresponding to the fastest predicted decay rate in the $0\nu\beta\beta$ channel. Good sensitivity limits (150 meV at 90% C.L.) will be obtained in 1–3 years. The duration of data talking will be determined by the strength of the signal, if any, and by the backgrounds. A possible upgrade to use enriched *Nd* is under consideration, but the practical and financial limitations on the enrichment technology available makes this a remote possibility at present.

The second phase will study solar neutrinos starting in 2015. SNOLAB is the deepest underground physics facility and the reduced muon flux (compared to other underground labs) is a key advantage. At SNOLAB depth, ^{11}C cosmogenic muon production is no longer a background for a measurement of the flux of 1.4 MeV *pep* and *CNO* solar neutrinos. The *pep* solar neutrinos then become not only a feasible goal for SNO+, but the most interesting solar neutrinos to study. This flux is predicted with a small uncertainty. A precise measure of the survival probability can thus be made and the measurement occurs near the energy where there is maximum sensitivity to new physics is arising in the neutrino sector. As a test of the neutrino-matter interaction (whether there is new neutrino physics beyond the MSW effect), SNO+ is the best foreseeable experiment proposed. Between 3 and 5 years are necessary to reach the ultimate sensitivity, again depending on the backgrounds.

4.3.2 EXO

The Enriched Xenon Observatory (EXO) collaboration is developing time projection chamber (TPC) technology to search for neutrinoless double beta decay of ^{136}Xe. The goal is to reach a sensitivity to $m_{\beta\beta}$ down to the few meV range with a tonne-scale detector. EXO's strategy involves three components evolving in parallel: a liquid-phase physics detector with 200 kg of 80% enriched Xenon, (EXO-200); a gas-phase prototype with a capacity of 10 kg (Xenon Electroluminescence Prototype or XEP); and a program to identify the daughter nucleus (barium tagging). EXO-200 will measure the $\beta\beta$ transition rate of the 2ν channel, which has not yet been observed and is required to determine the ultimate sensitivity of the full EXO detector. EXO-200 will also search for the 0ν channel with a sensitivity to $m_{\beta\beta}$ of 150 meV, probing the mass range where members of the Heidelberg–Moscow collaboration claim to have observed this transition in ^{76}Ge. The experience gained with the operation of EXO-200 and XEP will set the criteria for the selection and design of a liquid or gas detector for full EXO.

Canadians have been involved since 2004 in EXO. The idea of a gaseous configuration of the full EXO detector has been discussed in the collaboration. Canadians have provided the resources and expertise (from OPAL) necessary to build a dedicated prototype. Other skills brought to EXO by the Canadians were in low background monitoring and mitigation of radioactivity. The Canadian group consists of 24 people, including six faculty at Carleton, Laurentian and SNOLAB, and forms one quarter of the collaboration. A Canadian PI serves as one of two analysis coordinators. Another serves as the calibration coordinator.

The EXO-200 detector is located at the Waste Isolation Pilot Plant near Carlsbad, New Mexico. The cylindrical TPC records both the ionisation and scintillation light generated in an event. Canadian contributions to EXO-200 are: primary engineering support; responsibility for the design, installation, and operation of calibration systems; in-line radon reduction; trace radioactivity measurements; xenon process systems support, lead shielding design and installation; muon veto installation; and Monte Carlo simulation and analysis. Assembly of EXO-200 is complete and the subsystems are being commissioned. Following initial calibrations in summer of 2010, EXO-200 will collect two years livetime of data.

With the Xenon Electroluminescence Prototype, EXO is pursuing a gas-phase option in parallel with EXO-200. While a gas detector would occupy a much larger volume, the tracking information allows for powerful single β event rejection (over 95%) and the possibility for a simpler barium tag. A 10-bar pressure vessel is being instrumented at Carleton to house the gas-phase TPC. The detector will use electroluminescence (EL) to convert the ionisation signal into a photon signal with a gain of approximately 500. The gas TPC will be assembled and commissioned through the fall of 2010. Following one year of operations at Carleton the detector will be moved underground at SNOLAB.

Canadians have provided the key ideas for a gas-phase barium tagging system, in which the ion is transported with electric fields to an exit nozzle in the TPC. A test system is under construction at Stanford with components and design support contributed by Canada. The R&D is expected to take two years. Once the proof of principle is obtained, the system will be integrated with XEP at SNOLAB.

EXO-200 will take data for 3–5 years. So 2013–2015 will be critical for EXO. Beyond the physics results, EXO-200 will have determined the backgrounds and ease/cost of operating a large liquid detector. At that point XEP will have answered similar questions for a gas detector. Designs for a liquid and a gas full EXO detector are underway. A decision on the technology choice for the full EXO experiment is expected by 2015.

4.3.3 T2K

T2K is a long-baseline neutrino oscillation experiment that studies oscillations of a ν_μ beam produced at the J-PARC accelerator in Tokai, Japan. The primary goal of T2K is to observe $\nu_\mu \to \nu_e$ oscillations by looking for an excess of electron neutrinos appearing in the far detector Super-Kamiokande, which sits 295 km away. The rate of this process is sensitive to the neutrino mixing angle θ_{13}, along with the CP violation parameter δ_{CP} and the sign of the mass hierarchy. A sophisticated near detector called ND280 measures the neutrino beam's flux and energy spectrum at its production point, including backgrounds to the ν_e appearance signal. T2K will also measure the atmospheric neutrino mixing parameters Δm^2_{23} and θ_{23} with much better precision. T2K will quantitatively test the standard oscillation formalism, look for evidence of non-standard neutrino interactions, and precisely measure several neutrino cross sections relevant to oscillation measurements that, in many cases, are not understood at the 20–30% level.

Canadians started working on the T2K project in 2000. In 2006 they received NSERC support to build the ND280's tracking sub-detectors – three TPCs and two fine-grained detectors (FGDs) – as well as an optical transition radiation beam monitor (OTR). The OTR detector was installed with the horn/target system in late 2008 and has been used in the neutrino beam line commissioning since April 2009. The TPCs and FGDs were installed in late 2009 and have been in continuous operation since. TRIUMF made significant contributions to both the beamline and detector construction as well as commissioning. The T2K collaboration comprises 276 physicists and 120 students from 12 countries. The Canadian group consists of 32 physicists (19 grant-eligible) and 14 students from 7 institutions. Canadians play leading roles in physics analysis, including holding the position of physics analysis coordinator for T2K's near detector, conveners of several analysis groups, and the ND280 run coordinator.

T2K recently completed its first year of successful operation, collecting commissioning data from December 2009-June 2010. Data analysis for an initial publication is underway. Beam will resume in

November 2010 at up to 150 kW of power. By summer 2011 T2K should have enough statistics to surpass the current CHOOZ limit on θ_{13}.

T2K will ultimately collect 750 kW $\times$ (5×10^7 s) of accumulated protons on target. By 2015 T2K is projected to have accumulated about half of its proposed exposure, giving a sensitivity to $\sin^2 2\theta_{13} < 0.009$ (90% C.L.). Two additional years of running at the peak beam power will allow T2K to achieve its proposed statistics, reaching an eventual sensitivity of $\sin^2 2\theta_{13} < 0.006$ by 2017. Over this period, the Canadian group's efforts will be focused on operations and maintenance of our detector contributions, calibration and analysis of data from these detectors, and a wide variety of contributions to higher-level physics analysis, including ν_e appearance and ν_μ disappearance. Initial efforts in contributing to analysis of T2K data from Super-K are already underway.

The future of T2K depends to a large extent on ν_e appearance results or θ_{13} information from other experiments. The search for leptonic CP violation, expressed as a difference between the $\nu_\mu \to \nu_e$ and the $\bar{\nu}_\mu \to \bar{\nu}_e$ probabilities, would motivate a follow-up measurement. Proposed experiments such as Hyper-Kamiokande in Japan and the LBNE (Fermilab→DUSEL) experiment in the US would use much larger far detectors and beam power upgrades to search for this matter-antimatter asymmetry. The Canadian T2K group is following these developments closely, and depending upon initial results from T2K could become involved in R&D for a phase 2 experiment in the 2013-2015 period, with construction of new detectors beginning after 2015.

4.4 Dark matter

The Canadian subatomic physics community is currently engaged in three direct dark matter searches, all eventually to be based at SNOLAB, as well as indirect observation searches with VERITAS or IceCube through gamma-ray or neutrino production from relic particle annihilation (see Section 4.5), and direct production searches at the LHC and, potentially, the ILC (see Section 4.1). Canadian theorists, particularly at Victoria and UBC, have also contributed to studies of dark matter detection prospects. In this section we outline the three direct dark matter search experiments.

4.4.1 DEAP

The DEAP (Dark Matter experiment using argon pulse-shape discrimination) detector uses liquid argon as a target material, searching for the spin-independent elastic recoils of Galactic halo WIMPs. DEAP currently has two phases: DEAP-I, a 7kg prototype used to assess background discrimination and to develop low background techniques, and DEAP-3600, the 3.6 tonne physics detector. The DEAP-3600 detector will achieve a sensitivity to WIMP-nucleon interactions with cross-sections down to 10^{-46} cm^2 per nucleon. This high sensitivity will be achieved from the very large target mass and the very low backgrounds possible in target and detector construction, self-shielding of background radiations and the radio-quiet environment of SNOLAB.

The design for the DEAP-3600 detector is a large spherical acrylic vessel filled with 3.6 tonnes of liquid argon, viewed by 266 photomultiplier tubes (PMTs) through acrylic light guides. The inner argon target is surrounded by 50 cm of acrylic, which acts as a passive neutron shield for neutrons generated in the photomultiplier array. Signals from the photomultiplier tubes are recorded using waveform digitisers, to allow pulse shape discrimination against remaining backgrounds, primarily the beta-radiations from ^{39}Ar decays. The DEAP-I prototype has demonstrated 10^8 discrimination between nuclear and electronic recoils in liquid argon, with future runs of DEAP-3600 expected to use argon depleted in ^{39}Ar to reduce this background.

The total capital requirement for the DEAP-3600 detector has been secured from CFI, the provinces of Ontario and Alberta, and the universities of Queens, and Alberta. The procurement of component parts is underway. Infrastructure construction for the support deck has been completed with an investment from the SNOLAB facility funding.

DEAP-3600 is a predominantly a Canadian project, with researchers from Alberta, Carleton, Laurentian, Queens and TRIUMF. Several US institutions (including MIT, Yale and Princeton) are connected to a broader collaboration including the CLEAN project. In total there are 12 Canadian researchers involved, at a level of 5 FTE, with an additional 32 postdocs, students, engineers and SNOLAB staff scientists.

4.4.2 PICASSO

The PICASSO (Project in CAnada Searching for Supersymmetric Objects) detector is a mature technology focused on the search for WIMPs through their spin-dependent coupling to target nuclei. Searches in the spin-dependent sector are motivated by the facts that WIMPs may favour spin-dependent interactions, leading to a first observation with these techniques, and the spin dependent and independent cross sections are largely uncorrelated thus limits from both provide a powerful tool for model diagnostics. The sensors comprise polymerised emulsions loaded with super-heated liquid fluorocarbons, C_4F_{10}, as the target nuclei, the ^{19}F having a highly enhanced nuclear form factor for spin dependent interactions. The detection of an interaction uses the bubble chamber principle, with acoustic readout of the signal. Due to the use of a light target nucleus ^{19}F and their very low energy threshold, the PICASSO sensors have high sensitivity to low mass WIMPs, below 15 GeV. Interest into very low mass was revived by the recent results of COGENT and DAMA. PICASSO is one of the few experiments with a calibrated nuclear recoil response down to 1.3 keV (lower than either XENON and CDMS). Finally, due to differences in the ionisation density of different incident radiations, the PICASSO sensors can be run in a gamma-blind mode, where the detectors are insensitive to interactions from background gamma and beta radiations. This substantially reduces the background rates and ensures only neutron and alpha backgrounds are of concern.

The present installation at SNOLAB comprises 32 detector modules, each loaded with C_4F_{10} in 4.5 litres of gel, corresponding to a target mass of 65g of ^{19}F for a total active mass of 2 kg. Four detectors are loaded into thermally and acoustically isolated chambers, that serve as a temperature stabilisation unit to 0.1°C, with a stack of eight such modules held within a water shield against ambient neutrons. This array has been operational since 2008, and is being relocated to the new Ladder Lab facility within SNOLAB during 2010. The 2009 analysis of data collected from the PICASSO array led to a world-best limit on the spin-dependent interaction cross-sections of WIMP particles on nuclei. For a neutralino mass of 24 GeV, an upper bound on the cross section was found at 0.16pb at 90% CL. Improvements in the backgrounds of the PICASSO modules are expected in future runs, with the development of a lower activity matrix for the super-heated droplets. In addition, discrimination between alpha activity from the detector material, and ambient neutron backgrounds, or WIMP signals, has been demonstrated by timing analysis of the acoustic signal.

PICASSO is primarily a Canadian experiment, with involvement from Alberta, Laurentian, Montréal, Queens and Bubble Technology Industries, Chalk River. International collaborators are Indiana South Bend (USA), Czech Technical University Prague (CZ) and the Saha Institute for Nuclear Physics (IN). In total there are 13 faculty involved, at a level of 4 FTE, with 20 students, post-docs and technicians.

4.4.3 SuperCDMS

The CDMS collaboration currently operates an array of thirty, 250g, low temperature germanium and silicon detectors, housed in five towers within a cryostat, at the Soudan underground facility in Minnesota. The detectors search for spin-independent elastic recoils of WIMPS off the Ge nuclei by searching for the ionisation and phonon signatures expected with this interaction. The ratio of these two signals give a strong background rejection, with additional surface beta interactions in the crystal rejected through pulse shape timing analysis of the ionisation signal. A recent analysis of data collected from 2007 and 2008 gave two events in the signal region of the detector, with an expected background of 0.9. If interpreted as a limit on the WIMP-nucleon cross-section, this allows the CDMS collaboration to set a 90% confident limit of 7×10^{-44} cm^2, for a WIMP mass of 70 GeV. Although statistically consistent with background, this indicates that additional improvements in background and discrimination are required. These aspects are the focus of the next generation experiment, SuperCDMS, to be located at SNOLAB.

New detector technologies are being explored for the future project, SuperCDMS, which will use larger crystals with a new electrode structure to further improve background rejection, specifically the low energy surface beta interactions. The detector size scales from 1 cm to 1 inch in thickness, with similar diameter crystals. The final objective of SuperCDMS is a detector mass of 150-200 kg, with this phase to be deployed at the greater depths of SNOLAB to remove potential cosmic-ray muon induced backgrounds in the larger array. In addition to the final deployment, a test facility for characterisation of these larger crystals will be developed at SNOLAB, using existing cryogenic equipment in a new shielded environment to be provided by the facility.

At present the SuperCDMS community in Canada comprises two faculty and six post-docs/students at Queens.

4.5 High-Energy Particle Astrophysics

The Canadian subatomic physics section of NSERC currently supports two projects in high-energy particle astrophysics: VERITAS and IceCube

4.5.1 VERITAS

VERITAS is an array of ground-based gamma-ray telescopes, using the stereoscopic imaging air Cherenkov technique, that has sensitivity to gamma-rays in the 100 GeV-10 TeV energy range. The Canadian effort on VERITAS consists of two faculty at McGill, along with two postdocs and five graduate students. The overall size of the collaboration is ~ 100 researchers. The Canadian VERITAS group has contributed the mirror mounts for the telescopes, trigger electronics, and a UV-LED calibration system, as well contributing to data analysis.

Canadian involvement in VERITAS grew out of an earlier project called STACEE, that addressed similar science using a lateral sampling air Cherenkov telescope. By using stereoscopic viewing of air showers to reject cosmic ray backgrounds and improve shower reconstruction VERITAS has achieved superior sensitivity to northern sky sources and has discovered many new sources of TeV-scale gamma-rays from a variety of sources. VERITAS began operations at full sensitivity in 2007.

The science topics addressed by VERITAS that are closest to particle physics include gamma-ray emission from dark matter annihilation in dwarf galaxies and other gravitational attractors, gamma-ray emission during the final stages of evaporation of primordial black holes, and energy-dependent velocities of high-energy gamma rays due to effects of quantum gravity. These topics have been explored with competitive levels of sensitivity but, as with searches for exotic phenomena at accelerators and in underground experiments, exclusion plots are so far the result.

VERITAS has just been approved for an upgrade. All 2000 PMTs in the four telescopes of the array will be replaced with new Hamamatsu Super Bialkali PMTs that have a 40% larger quantum efficiency. This will result in an improved sensitivity and lower energy threshold. The new PMTs will be installed in the summer of 2012 and the upgraded detector will run until at least 2015. VERITAS will likely continue beyond that time frame especially if the recently launched, and highly successful, Fermi satellite (built by particle physicists from SLAC) continues to operate; there are many reasons to have complementary detectors operating concurrently.

The community of very-high-energy gamma-ray astrophysicists has come together to propose the next generation of detectors. It will likely be a single, large array of telescopes similar to the VERITAS design. A European initiative, the Cherenkov Telescope Array (CTA), has the most momentum at present and indeed may end up as the only player since the US-based project, AGIS, has just joined the CTA collaboration as a bloc. The project will cost several hundred million dollars and will be built in the southern hemisphere. The collaboration will include several hundred members. It is not clear at present whether there will be any Canadian involvement in this project.

4.5.2 IceCube

IceCube is a detector for high energy neutrinos ($E_\nu > 10$ GeV) embedded in the Antarctic ice at the South Pole. IceCube uses strings of photomultiplier tubes to sample Cherenkov light produced by neutrino interactions in the ice, and the direction, energy, and possibly flavour of the neutrino can then be reconstructed from the pattern of detected light.

IceCube focuses on similar scientific questions to those addressed by VERITAS in a somewhat complementary way. The detection of high-energy neutrinos from an astrophysical source such as an AGN would be indicative of the acceleration of hadrons inside that source, and could resolve longstanding questions about whether AGN jets are hadronic or leptonic in nature. While the universe is opaque to high-energy gamma-rays on large (MPc) distance scales, neutrinos from more distant sources can reach Earth unimpeded. To date, however, no sources of astrophysical neutrinos have been detected.

The Canadian effort on IceCube began in 2009, and presently consists of a single faculty member and students at Alberta. At present no other Canadian scientists have expressed an interest in joining IceCube, and the PI, who worked on IceCube as a postdoctoral fellow in the US, has indicated his intent to move to DEAP in the coming years.

4.6 Beyond the standard model symmetries

The physics program of the particle physics community is focused on the search for new physics beyond the SM. The core of the program is based around a number of large accelerator-based projects such as ATLAS, T2K and SuperB together the SNOLAB experiments. In addition, there are a number of smaller projects focused on specific aspects or extensions of the SM that can only be addressed using dedicated experiments.

This section describes three projects where Canadians play a key role: Ultra-cold Neutrons at TRIUMF, the MoEDAL experiment at CERN and the muon $g-2$ project at J-PARC.

4.6.1 Ultra-cold neutrons at TRIUMF

The aim of the project is to create the world's highest density source of ultra-cold neutrons (UCN) to make a new measurement of the electric dipole moment of the neutron (EDM). EDMs of fundamental particles are forbidden by time-reversal symmetry, however, the small amount of CP violation in the SM leads to very tiny EDMs. In many models of physics beyond the SM, new sources of CP violation are present and these can result in large EDM values. Such models often naturally generate neutron EDMs at the 10^{-27} e-cm level, just below the present experimental sensitivity.

UCNs are neutrons with such low energies that they are totally reflected from the surfaces of a variety of materials. UCNs can be highly polarised and stored in material bottles for long periods of time, allowing low-field NMR experiments to be conducted with high precision. These methods form the basis of the best neutron EDM measurements to date.

A host of other physics experiments are also envisioned at the UCN source at TRIUMF. For example, one can probe short-distance gravity from neutron quantum states in a gravity well or make an improved neutron lifetime measurement. It may be possible to use the UCN source to search for $n\bar{n}$ oscillations, use it as a free neutron target or study low-energy excitations on material surfaces.

The project is presently a collaborative effort between researchers in Japan, Canada, and the US. The group received funding in June 2009 from both CFI and Japan, involves three particle physics investigators and a larger contingent from the nuclear physics community and is currently investigating and prototyping the experimental system with activities in Japan and Canada. It is expected that the experiment will take its first beam in TRIUMF in 2014-2015.

4.6.2 MoEDAL at CERN

MoEDAL (Monopole and Exotic detector at the LHC) will search for electrically charged magnetic monopoles and other highly-ionising stable or pseudo-stable massive particles (SMPs) at the LHC. An SMP can be one or many states and carry a new conserved, global quantum number. For example, there are states in SUSY with R-parity or some extra dimension models that fall into this category. The lightest SMP is expected to be stable and the higher-lying states may also be stable or meta-stable. In addition, MoEDAL is sensitive to SMPs with multiple electric charge such as the black hole remnant, or long-lived doubly charged Higgs bosons.

The MoEDAL experiment will complement the search capabilities of the general purpose LHC detectors allowing searches for electrically and/or magnetically charged SMPs with high sensitivity. It is anticipated that an SMP produced at the LHC will have a velocity significantly slower than the speed of light. The large LHC experiments are designed to detect particles produced with a velocity near the speed of light.

The MoEDAL detector is comprised of an array of plastic Nuclear Track Detectors (NTD) deployed around the intersection region of the LHCb detector. The array consists of NTD stacks attached to the walls and ceiling of the cavern. When a charged particle crosses a plastic nuclear track detector it produces damage at the level of polymeric bounds in a small cylindrical region around its trajectory. The damage produced is dependent on the energy released and is a function of the charge Z and velocity of the incident highly ionising particle. The subsequent etching of the nuclear track detectors leads to the formation of etch-pit cones. These conical pits are of micrometer dimensions and are observed with an optical microscope with their size and shape giving information about charge, energy and direction of motion of the incident ion.

The MoEDAL Collaboration currently consists of 26 physicists from seven countries and nine institutions, and is led by Alberta with a Canadian spokesman. A small portion of the MoEDAL array was installed as a test deployment in November 2009. In December 2010 the detector stacks will be extracted for analysis and a new set of stacks will be deployed for one year. The plan is run with a full detector at each energy point attained by the LHC, ending with a high luminosity run at the nominal LHC collision energy of 14 TeV. The envisaged lifetime of the experiment is approximately 5 years.

4.6.3 Muon g-2 at J-PARC

The measurement of the muon $g-2$ is a key result in establishing the validity of quantum electrodynamics. Further, the result is sensitive to new particles such as additional gauge bosons, supersymmetric particles or excited leptons as any new particle that couples to the muon would modify the value of $a_\mu = (g_\mu - 2)/2$. Currently, the best experimental value is from E821 at BNL $\alpha_\mu^{E821} = (116\,592\,089 \pm 63) \times 10^{-11}$ and is slightly different than the theoretical prediction $\alpha_\mu^{SM} = (116\,591\,834 \pm 49) \times 10^{-11}$ by approximately three standard deviations. The leading theoretical uncertainty of 40×10^{-11} arises from hadronic vacuum polarisation. The theory uses low energy $e^+e^- \rightarrow \pi^+\pi^-$ data or $\tau^- \rightarrow \pi^-\pi^-\nu_\tau$ decays to evaluate this term. The two sets of data give a slightly different correction term, however, new e^+e^- and τ measurements are expected to reduce the theoretical uncertainty by a factor of two. A new measurement with improved precision is viewed as an important step.

The muon $g-2$ measurement being proposed will take beam at J-PARC and involves researchers from TRIUMF. One of the novel and challenging aspects of the project is the need to build a source of ultra-cold muons that can then be accelerated. The technique proposed involves stopping a beam of muons in a target where the muons form polarised, room temperature, muonion. A high-power laser ionises the muonion producing thermal, polarised muons that are then accelerated to give a beam of very low emittance.

The TRIUMF group has expertise in low-energy muon physics and, in particular, the production of polarised muonium required for the source of the proposed ultra-cold muon beam. The TRIUMF group and a number of their collaborators are proposing a set of measurements at TRIUMF to understand the rates and mechanism of muonion production.

A proposal was submitted to J-PARC in December 2009. After approval, the Canadian group would request funds to participate in the project. A new muon beam line at J-PARC would need to be built and the estimated timescale for first beam is 2013.

4.7 Dark energy

Recently a small effort has developed in Canada, led by a particle physicist, to apply calibration techniques developed for particle physics calorimeters to the problem of developing a stable calibration source for ground-based photometry of high-Z supernova in order to probe dark energy. Traditional astronomical photometry relies on measurements of "standard candles" to determine the effects of atmospheric attenuation, but since few stars are truly stable in their light output to $< 1\%$ these calibrations are limited in their accuracy and are a major uncertainty for future efforts to exploit high-Z supernova for constraining the nature of dark energy.

The BALCAL proposal is to place a very stable, calibrated light source above the Earth's atmosphere, initially on a high-altitude balloon, to provide orders of magnitude improvement in the calibration standards for ground-based photometry. Payload construction and test flights are planned for the 2011-2013 period, with R&D towards a future satellite-based mission planned in the 2013-2015 period. The BALCAL proposal includes several groups in the US, primarily from the astronomy and metrology community, and it is not yet clear in the Canadian context whether BALCAL fits cleanly within the mandate of the Subatomic Physics Evaluation Section as opposed to the Astronomy Evaluation Section.

4.8 Theory

Theoretical particle physics aims to create a unified understanding based on the data from the full range of current and past experiments.

The procedural structure of theoretical particle physics is generally as follows. First a model is constructed, usually consistent with tested frameworks such as quantum field theory or Lorentz invariance. The model may be designed to account for unexplained phenomena such as dark matter, to address conceptual problems in the Standard Model such as the large unstable hierarchy between the scale of weak interactions and that of quantum gravity, or to unify gravity with the other forces in a quantum-mechanical framework. The model then needs to be tested. This is done by working out the predictions of the model for past experiments—e.g., exclusion limits on new particles, precision electroweak or flavour physics, or cosmological measurements—and by proposing new measurements or analysis techniques for ongoing or future experiments to discover and/or distinguish new physics possibilities. These predictions sometimes require detailed higher-order calculations or computer simulations of strongly-interacting theories on a lattice. Simultaneously, the expected signals from known Standard Model physics need to be computed to sufficiently high precision. Experiments may lead to unexpected results, in which case the role of theory is to construct models to explain these results, ideally in the framework of some underlying principle of nature, and propose different measurements to test the framework. A frequent broad theme is finding inter-relations among the predictions for a broad range of experiments, from cosmology to collider physics to high-precision symmetry tests, which allow models to be tested from many complementary directions.

The activities of the Canadian theoretical particle physics community can be roughly subdivided as follows. In many cases, individual theorists will work in two or more of these areas. Statistics are for grant-eligible theorists who are or would be classified as part of the NSERC subatomic physics envelope.

Phenomenology comes in several flavours. The more conservative kind involves improving the predictions of accepted theories like QCD or the SU(2) electroweak theory in the context of experimental measurements. The more speculative kind involves building models beyond the Standard Model to address its deficiencies and making predictions for possible future measurements. Both kinds are clearly necessary for the understanding of any new physics which might be discovered at the LHC or elsewhere. The first kind is needed for understanding the backgrounds, while the second is needed to give a detailed framework against which to test departures from the Standard Model. A key component of this program is the development of techniques to extract the underlying model parameters from data. Most current model-building is motivated to solve the hierarchy problem, explain dark matter, and/or provide naturally small neutrino masses. The study and classification of experimental signatures from a wide variety of models also provides a framework for future model-building to explain any new discoveries. About 40% of the Canadian theoretical particle physics community is involved in phenomenology.

Astroparticle physics is closely related to phenomenology. This area of theoretical research marries particle physics with astrophysical techniques to study high-energy cosmic rays, neutrinos from supernovae, and potential signatures of dark matter, as well as using astronomical measurements like the primordial nuclear abundances to constrain new physics models. A handful of Canadian theorists specialise in astroparticle physics, which has obvious links to SNOLAB's experimental programme.

Lattice field theory describes the solution of strongly-coupled theories through a discretised numerical implementation. The most familiar example is lattice QCD, which is used to predict hadron masses and structure constants based on QCD. These predictions are a key ingredient for the experimental study of the flavour structure of quarks. Lattice techniques have more recently been applied to other strongly-coupled field theories, with applications to strongly-coupled electroweak symmetry breaking as well as more general mathematical understanding of the structure of quantum field theories. About 10% of the Canadian theoretical particle physics community specialises in lattice field theory.

Quantum field theory involves the general exploration of the properties of (usually relativistic) quantum field theories. The motivation for this work comes from one of the other categories, or from the basic fact that quantum field theories form the foundation of our theoretical understanding of nature, and so their properties deserve study in their own right. In particular, the study of strongly-coupled gauge theories has recently taken off due to new "holographic" techniques developed as an offshoot of string theory. Another motivation can come from potential applications to other areas of physics, where similar field-theoretic techniques can often apply. About 30% of the Canadian theoretical particle physics community works in this area.

String theory and quantum gravity represent theoretical attempts to create a unified description of gravity with the other forces in a quantum mechanical framework. In their purest form, string theory and quantum gravity provide a natural description only near the Planck scale, making them practically untestable except possibly through cosmology. In the past decade, however, it was realised that the quantum gravity scale could be near the TeV scale if extra dimensions are present. For example, the idea of large extra dimensions has strong links to both gravitation and to particle physics, since it predicts both modifications to the gravitational force law at submillimeter distances, and new signatures for collider physics via Kaluza-Klein states and even TeV-scale black holes. Techniques from string theory have been taken up by the quantum field theory and phenomenology communities and are yielding important applications to the understanding of strongly-coupled gauge theories like QCD. One example is the application of the AdS/CFT correspondence, that relates physics in a negatively-curved (anti–de Sitter) higher-dimensional spacetime to that of a strongly-coupled conformal field theory on the flat boundary of the spacetime, to heavy-ion collider physics, QCD bound states, and models of dynamical electroweak symmetry breaking (technicolour). About 25% of the Canadian theoretical particle physics community works in string theory or quantum gravity.

Cosmology, in the particle physics context, focuses on possible explanations for early-universe inflation, late-time dark energy, and observational tests of unified models of quantum gravity through the cosmic microwave background and gravitational waves. Some components are the avoidance of the unphysical big-bang singularity predicted in non-quantised general relativity and possible explanations for the suspiciously convenient values of physical constants. Some approaches, such as brane inflation, are motivated by string theory and extra-dimensional models. About 10% of the Canadian theoretical particle physics community works on cosmology.

The main expenses of the theory community are student and postdoc salaries and travel to conferences and workshops. Topical workshops have been organised on an ad hoc basis by groups within the theory community from across the country, over the past several years. These have been particularly valuable for facilitating interaction and collaboration and are of mutual benefit to the theoretical and experimental particle physics communities. Some subfields, particularly lattice and theorists doing higher-order phenomenological calculations, also benefit from the tremendous expansion of computing facilities in Canada over the last five years.

5 The Canadian particle physics community

Canada's accomplishments and future potential in particle physics are driven primarily by the quality and size of the particle physics community. Here we will examine the demographics of the particle physics community in Canada and the relationship between the experimental and theory communities within our programme.

5.1 University groups

In the following we characterise the roles university groups play in the large-scale experimental efforts we undertake in particle physics, and explore the continued growth in the numbers of faculty and HQP working in particle physics within the community.

5.1.1 Canada Research Chairs

Since the beginning of the program in 2000, ten Canada Research Chairs have been appointed in areas directly related to particle physics research. The majority of these were new junior faculty appointments, representing a significant contribution to the overall growth in the HEP community during that period. The remainder were new appointments from outside Canada into more senior positions while others were appointments of existing faculty at Canadian institutions into CRC positions. Faculty holding CRC positions currently contribute to many of the core projects of the IPP program and the high priority research areas identified by the last NSERC LRP exercise, including SNO, DEAP, T2K, ATLAS, ILC R&D, the Tevatron experiments and theory. These positions have proven an effective incentive to recruiting and retaining talented researchers within the Canadian particle physics community.

5.1.2 University expansion in particle physics over the last five years

There are 14 institutional members of the Institute of Particle Physics, 12 university groups and two research institutions. Each institute was asked to complete a brief survey outlining how the composition of their group had changed since the start of 2005 i.e. since the last five year plan. Each group was asked to provide the current number of faculty, RAs, PDFs and graduate students in the group along with the change in that number compared to five years ago. In addition the number of PhD and MSc degrees awarded are given along with the hiring areas for new faculty. The data from the groups who responded is shown in table 2[†]. Note that since TRIUMF and the Perimeter Institute do not grant degrees the students who are co-supervised by faculty there are counted in their associated university row.

These data show that the field is growing vigorously with an absolute increase of over 10% in the number of faculty Canada-wide compared to five years ago. The breakdown of the areas where new faculty have been hired is shown in tables 1 and 3. These tables include data for all new faculty hires i.e. both replacement for retirements as well as for newly created positions. The data clearly show that the main areas are Collider/ATLAS, theory and astro-particle which, as expected, closely align with the stated research priority areas outlined in this document. Overall Canadian universities continue to view particle physics as an area for growth and investment.

In addition the combined number of RAs and PDFs has increased by over 25% and the number of students by 20%, over twice the rate of increase in the number of faculty. We take this as a measure of the

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[†] These numbers do not include smaller universities that are not institutional members of the IPP.

Year	Hire	Subfield	Institution
2005	David Asner	Collider/Flavour	Carleton (Move to PNNL in 2010)
	Mauricio Barbi	Neutrinos/Collider	Regina
	Leonid Kurchaninov	Detectors	TRIUMF
	Roger Moore	Collider	Alberta
	Fabrice Retiere	Detectors	TRIUMF
	Isabel Trigger	Collider	TRIUMF
	Richard Teuscher	Collider	IPP/Toronto
2006	Justin Albert	Collider/Flavour	Victoria
	Kamal Benslama	Collider	Regina
	Colin Gay	Collider	UBC
	Kevin Graham	Underground	Carleton
	Wolfgang Rau	Underground	Queens
	Ubi Wichoski	Underground	Laurentian
2007	Richard Ford	Underground	SNOLAB
	Aksel Hallin	Underground	Alberta
	Chris Jillings	Underground	SNOLAB
	Hirohisa Tanaka	Neutrinos	IPP/UBC
2008	Anadi Canepa	Collider	TRIUMF
	Carsten Krauss	Underground	Alberta
	Bernd Stelzer	Collider	SFU
	Oliver Stelzer-Chilton	Collider	TRIUMF
2009	Phillipe Di Stefano	Underground	Queens
	Darren Grant	Underground	Alberta
	Christine Kraus	Underground	Laurentian
	Nigel Smith	Underground	SNOLAB

Table 1: Faculty hires in experimental particle physics in Canada since 2005

	Faculty		RAs		PDFs		Students		PhD's	MSc's
Institute	#	Δ	#	Δ	#	Δ	#	Δ	awarded	awarded
Alberta	10	+1	6	+2	8	+4	12	-3	9	8
Carleton	12	-	8	-0.5	0	-	19	+7	6	10
Laurentian	4	+1	2	+2	4	+1	3	+1	-	5
McGill	13	-	2	-	11.5	+3.5	46	+20	15	28
Montreal	6.5	-2.5	1	-2	5	+1.5	17	-9	11	31
Perimeter	9	+5	0	-	19	+5	9	-6	$0^\dagger$	$0^\dagger$
Queen's	6	+2	3	-	7	+1	14	+2	5	6
Regina	—— Declined to provide data ——									
SFU	4	+1	1	-	1	-1	12	+3	3	2
Toronto	12	-1	4	+2	5	+2	22	+5	13	9
TRIUMF	23	+1	13	+5	0	-	0	-	$0^\dagger$	$0^\dagger$
UBC	16	+3	9	+1	9	+5	43	+13	16	37
Victoria	9	+3	6	+1	6	+2	31	+19	6	16
W. Ontario	2	-1	0	-	1	-	3	-3	5	2
York	7	+2	3	-	1.5	+0.5	9	-	5	7
TOTALS	133.5	+14.5	58	+10.5	78	+24.5	240	+49	94	161

Table 2: Data showing how the number of particle physics researchers, both experiment and theory, has grown over the past 5 years. The numbers in the table are the current numbers of faculty, RAs etc. at each institute, with the change in that number since 2005 shown next to it. The number of degrees awarded over the past 5 years is also shown. †TRIUMF and the Perimeter Institute are not degree granting institutions.

increase in research intensity over the last five years, that has followed from an even larger increase in the number of faculty in the period 2001-2005 (when 43 new faculty were hired, compared to 30 in the period 2006-2010).

This growth in the community has not been matched by growth in the available funding in the NSERC SAP envelope for particle physics. More researchers are competing for a fixed pot of money, and the increase in the number of HQP is putting significant strain on the community's ability to fund experiments, as outlined in Section 6.2. The result is an increasingly untenable pressure on the SAP envelope, and a financial limitation on how many HQP can be trained within the SAP program, despite the scientific potential to involve many more students and research associates. More discussion of the scale of these funding pressures will be discussed in Section 8.1.

5.2 IPP research scientists

The Institute of Particle Physics employs eight Research Scientists as part of its primary research mission. These scientists hold grant-eligible appointments at IPP member institutions and focus their research on projects identified by the IPP as the core of the Canadian particle physics programme.

Currently, two scientists are affiliated with each of UBC, McGill, Toronto and Victoria, with the most recently hired scientist (H. Tanaka) joining UBC in September 2007. Because these scientists are not regular members of the teaching faculty they are engaged full time in research while remaining mainly free of schedule constraints associated with teaching and university administrative responsibilities.

These positions are in many ways analogous to those of laboratory staff scientists in other countries, except that they are distributed across university groups rather than based at a Canadian HEP laboratory. A similar system can be found in Italy in the INFN, albeit on a much larger scale than the IPP. Since many of the IPP projects are at international laboratories, this distributed model has proven very effective. The IPP Scientists are able to spend significant time at the laboratory while maintaining a strong coupling to their university groups. As grant-eligible researchers with university affiliations, IPP scientists are able to initiate and lead research efforts and supervise graduate students and postdocs. The participation of an IPP scientist in a large project can provide the critical mass of personnel to a relatively small (compared with the scale of the collaboration) Canadian group leveraging substantial research contributions within the collaboration. For example, this has been the case for the ATLAS collaboration, where the contributions of R. McPherson, R. Teuscher and P. Krieger (now faculty at Toronto) have enormously benefited the project and enhanced the overall impact of the Canadian group within the international ATLAS collaboration. All three played extremely valuable roles during the construction and commissioning phases of ATLAS, benefiting from the ability to spend substantial periods of their time at CERN. Similarly, F. Corriveau has led Canadian efforts in advanced calorimetry R&D, primarily aimed at contributions to a future ILC detector.

IPP Scientists are currently active in several of the core Canadian particle physics projects as identified by the IPP, with three scientists participating in the BABAR experiment at SLAC (C. Hearty, S. Robertson and R. Sobie), two with ZEUS at DESY (F. Corriveau and J. Martin), three with the T2K experiment in Japan (C. Hearty, J. Martin and H. Tanaka) and five involved, to varying degrees, in ATLAS (F. Corriveau, R. McPherson, S. Robertson, R. Sobie and R. Teuscher). In a number of instances, notably ATLAS-Canada, BABAR-Canada and ZEUS-Canada, IPP scientists (R. McPherson, C. Hearty and J. Martin, respectively) are the project grant holders and spokesperson for the Canadian groups, a recognition of their international scientific stature.

Because they are able maintain a high level of research commitment throughout the academic year, potentially spending a significant fraction of their time away from their home institutions, IPP scientists provide a highly visible faculty-level presence at experimental facilities around the world. Current IPP scientists have served as the overall physics coordinators of the OPAL (R. McPherson), ZEUS (J. Martin) and BABAR (C. Hearty) experiments, and are currently the physics coordinators of the BABAR (S. Robertson) and T2K (H. Tanaka) experiments. IPP scientists have also held positions as deputy spokespersons, run coordinators, physics group conveners and other senior management roles within their respective collaborations. R. Teuscher and S. Robertson are currently resident full time at CERN and SLAC, respectively.

IPP Scientists have also contributed substantially to HEP research activities beyond the scope of their research collaborations, holding leadership roles in Canadian and international organisations which support HEP research. For example, J. Martin chaired the NSERC subatomic grant selection committee in 2007 and has served on the LHC Experiments Committee (LHCC), while R. Sobie has chaired the ICFA Panel on Computing (IHEPCCC) and continues to serve as Director of HEPNET/Canada. C. Hearty and R. Sobie were the principle organisers of the Flavour Physics & CP Violation (FPCP 2006) and the International Conference on Computing in High Energy and Nuclear Physics (CHEP'07), respectively. These important roles not only directly benefit Canadian particle physics research, but also enhance the profile of Canadian high energy physics within the international community.

Maintaining support for the IPP research scientist program is critical for the health of the Canadian particle physics community.

5.3 The role of theory in the universities

There are currently 74 grant-eligible theorists in the Canadian particle physics community[‡], making up about 1/3 of the grant-eligible Canadian particle physicist population. The majority are employed by universities, with two at TRIUMF and 9 at Perimeter Institute. Of the 13 new theorists who have joined the Canadian community since 2005 (Table 3), about half are phenomenologists, with the rest split among string theory, quantum field theory, and cosmology.

In addition to theoretical research and the training of theory graduate students, theorists at universities contribute to the Canadian particle physics program in a number of ways. First, theorists tend to teach the graduate-level courses like quantum field theory, that are crucial to both experimental and theory students. Theorists also contribute pedagogical lectures at graduate-level schools like the TRIUMF Summer Institute and Lake Louise Winter Institute. Second, theorists supervise undergraduate honours projects that provide a pipeline for future graduate students into subatomic physics, particularly at small institutions without experimentalists on the faculty. Finally, theorists with phenomenological interests based at the universities interact with experimental colleagues, expediting the flow of ideas about what measurements to make to test new models and how models are constrained by existing measurements, providing high-precision predictions for Standard Model processes, and constructing models that attempt to explain unexpected signals with associated suggestions for new measurements.

One significant issue facing the theory community is the relative isolation of theorists, particularly at smaller institutions. This presents a challenge for hiring postdoctoral research associates and graduate students. Larger groups can pool grants to hire postdocs and can provide a safety net for graduate students in case of unexpected grant cuts. These options are usually unavailable to isolated theorists, resulting in untapped capacity for graduate student supervision and research productivity.

Isolation of theorists is ameliorated by self-organised interaction, e.g., through topical workshops that

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[‡] This count includes theorists at smaller institutions that are not listed in Table 2

Year	Theorist	Subfield	Institution
2005	Robert Brandenberger	cosmology	McGill
	Freddy Cachazo	quantum field theory/strings	Perimeter
	Keshav Dasgupta	string theory	McGill
	Justin Khoury	cosmology	Perimeter (moved to U.Penn in 2009)
	Heather Logan	phenomenology	Carleton
	Adam Ritz	phenomenology	Victoria
2006	Joanna Karczmarek	string theory	UBC
	Alex Maloney	quantum gravity/strings	McGill
	Kris Sigurdson	astroparticle/cosmology	UBC
2007	Pavel Kovtun	quantum field theory/strings	Victoria
	Alexander Penin	phenomenology	Alberta
2008	David Morrissey	phenomenology	TRIUMF
	Veronica Sanz	phenomenology	York
2009	Thomas Gregoire	phenomenology	Carleton
2010	Davide Gaiotto	string theory	Perimeter
	Philip Schuster	phenomenology	Perimeter
	Natalia Toro	phenomenology	Perimeter
	Johannes Walcher	string theory	McGill

Table 3: Theorist hires since 2005.

allow exchange of ideas and formation of new collaborations. Resources for organising theory workshops tend to be scarce at the universities, suggesting an important role for the conference infrastructure at TRIUMF and Perimeter Institute. In recent years TRIUMF has hosted a handful of phenomenology workshops. Perimeter Institute also holds a significant number of workshops on diverse topics, though participation in these has tended to be by invitation only.

6 Structural challenges facing Canadian particle physics

Here we focus attention on structural issues relating to funding and resource allocation within the Canadian particle physics community, along with the challenges these create for Canadian researchers. These include:

- The relatively large cost and difficulty of securing stable funding for SNOLAB operations;
- The evolution and oversubscription of NSERC's SAP envelope, which funds most particle physics in Canada;
- The growth of CFI as an alternate funding agency for capital costs that is outside the scope of the community's long-range planning exercise;
- Changes to NSERC's MRS programme guidelines that undercut the particle physics community's ability to benefit from MRS grants;

- The extremely tight funding environment at TRIUMF, which limits its ability to support particle physics projects in Canada;
- Questions about whether Canada should engage with CERN to pursue a more formal status, and the challenge of funding such status.

6.1 SNOLAB operational support

The CFI programme (Section 6.3) has delivered substantial capital funding to Major Infrastructures for Science and Technology (MIST) throughout Canada. This has transformed the research infrastructure environment nationally and internationally, allowing Canada to compete with the best research facilities in the world. A $40M CFI award provided the majority of funding for the $60M development of SNOLAB, the conversion of the infrastructure extant from SNO at the Creighton nickel mine near Sudbury, into the deepest, cleanest underground facility in the world. Additional funding for the construction phase was generated from several sources: FedNOR, Ontario Innovation Trust and the Northern Ontario Heritage Fund.

Operational support for SNOLAB requires $6M cash per year, which does not include experiment costs that must be secured separately by the collaborating groups. Up to the present time, operational support funding has been obtained on an ad-hoc basis from several sources including NSERC SAP MRS and ad-hoc grants, the CFI IOF and a recent ad-hoc grant, Ontario ORF-RE support and funds from member universities. Significant in-kind support is also derived from Vale, the host company within whose mine SNOLAB is located. This provides significant in-kind matching support for SNOLAB operations necessary to maintain federal and provincial funding

Operational funding has been maintained, so far, without significant grants from the NSERC SAP envelope. This is essential to ensure that SNOLAB operational funding does not compromise the experiments it hosts, or vice versa, allowing the development of a vibrant Canadian underground physics experimental programme. Use of the SAP envelope to support SNOLAB operations would also undermine the wider SAP research programme. Although it is tempting to pit facility operational and development costs against the experiments they support, international precedents exist where this has had unforeseen, and unfortunate, consequences, leading to funding restrictions and stagnation across the programme. The potential benefit of direct competition for funds between lab operations and experiment construction, to ensure that the overall science community and stakeholder objectives are delivered in a co-ordinated and consistent way, can be addressed through coordinated reviews and oversight.

SNOLAB is not the only MIST project in Canada seeking stable operational funding. Other CFI initiatives such as Neptune, the Amundsen ice breaker, and the Canadian Light Source all face similar issues related to attracting operational funding. As a counter-point, TRIUMF has a well established operational funding mechanism through the NRC, due to historical precedence and scale. The overall funding model for the operation of Canadian MIST needs to be appropriate to the infrastructure being funded, allowing oversight and review during the full project life-cycle of the MIST, accounting for eligibility criteria of both federal and provincial funding mechanisms.

SNOLAB has taken advantage of a variety of funding streams with different eligibility criteria in order to provide full coverage of operational costs. For example, SNOLAB staff scientists are not funded from NSERC funds, allowing them to be NSERC grant-eligible like their peers at TRIUMF and the IPP. The preferred solution for operational support would be to simplify eligibility criteria, that are currently predicated on the assumption there are additional funding streams in place for several flavours of ineligible on-site expenses, for example the indirect costs of research support received by Universities based on the total amount of grant funding awarded to researchers on a given campus. SNOLAB institutions have agreed to ad-hoc transfers of these funds to Sudbury, to support laboratory operational costs. A systematic evaluation of this kind of support for off-campus MIST facilities in Canada is needed.

Discussion has been on-going with NSERC, CFI and Industry Canada on a longer-term solution for SNOLAB operational funds. Following the CFI ad-hoc support for SNOLAB operations, that matches the Ontario ORF-RE support, SNOLAB operations are secured through March 2012. Beyond this time frame the hope is that a co-ordinated solution to the CFI-initiated MIST operations will be found from outside the NSERC SAP envelope for SNOLAB. The Tier1 centre at TRIUMF is another of the MIST projects funded by the CFI that should also be eligible for operating support through this new mechanism. A concrete proposal, from the CFI, to review, oversee and fund MIST operations, in five-year cycles – taking inspiration from the successful TRIUMF model – is expected in the fall of 2010. The LRPC should be in a position to review the guidelines for this new program, assess how they will impact the situation and comment on the ramifications for sub-atomic physics in Canada.

The IPP believes operating costs of future MIST construction or upgrades should be incorporated into any viable solution. Accordingly the full life-cycle of a MIST must be addressed, including construction, upgrade and de-commissioning when the science return is no longer world-class or no longer consistent with Canadian science community's objectives. We look forward the definition of this programme in the hopes that it will address the challenges faced by the large number of MIST projects currently seeking stable operating support. We understand that this programme could be rolled out in the next six months, well within the LRP deliberation period and thus the LRP report should be a in a better position to assess how this new program could affect our science, and priorities, going forward.

As emphasised during the last LRP exercise, the NSERC SAP envelope is not large enough to support SNOLAB operations. Any attempt to force even a significant fraction of the \$6M/year operations cost of the lab into the existing SAP envelope would effectively destroy subatomic physics in Canada.

6.2 The evolution of the SAP envelope

Subatomic physics and thus particle physics research in Canada has benefited tremendously from the establishment of the SAP envelope in the early 1990s. Given the long-term nature of the projects we undertake, having the ability to trade off capital and operating funding over periods of several years has provided us with significant flexibility as our projects move from 5-10 year construction periods into decade and longer operations phases. While ten or more years ago it might have been argued that our portfolio of projects might naturally average out these fluctuations – as some projects were under construction others were taking data and producing physics – it is now clear that we can expect, more and more often, to face 5-10 year gaps between construction of successive projects. Thus we may come to rely on the strategic flexibility the envelope provides us even more than we have in the past.

Figure 6 shows the evolution of the operating grants (blue circles), equipment (red squares) and MFA/MRS (black triangles) over the last twelve years. There are several features to this graph. The bulk of the funding was dedicated to support the operations of the various projects, both those taking data (SNO, ZEUS, BaBar, CDF, etc.) and those under construction (ATLAS, T2K, PICASSO, DEAP, SNO+, etc.). One sees a clear and steady increase in the fraction of the envelope devoted to operations over this period. This should not be a surprise. The last LRP made very clear the effects that the arrival of the Canada Research Chairs and the echo-boom replacement of university faculty hired in the late 1960s throughout the decade were expected to have, and we can now see that there has been a marked effect on the research intensity of our community. The younger faculty, working on exciting particle physics projects, have attracted and trained almost a factor of two more graduate students in this decade than the previous one. While the corresponding increase in the number of "direct-to-student" scholarships has helped, tuitions have more than doubled over the past decade while university scholarship support has stagnated and the cost of living has increased by at least 50%. The result is, as predicted in the last SAP LRP, tremendous pressure on operating budgets. The reaction of the GSCs and Evaluation Section is apparent in the graph.

Turning to the capital investments Canadian researchers have made over the past decade, we see, in the early 2000s, the tail end of our last large particle physics capital investment – the ATLAS construction MIG of $14M – over 5 years tailing off in 2003/04. Over the past decade we've made smaller investments in K0Pi0, BaBar, and a number of prototypes for SNOLAB experiments and the ILC. The capital contribution to the T2K experiment between 2006 and 2008 resulted in a modest increase in the equipment funding requested/required by the community (or available to them based on other constraints on the envelope) to achieve their long term particle physics goals. The most striking trend is over the last three years where, despite the fact we've been able to secure funding for the construction of two major SNOLAB experiments (SNO+ and DEAP), these resources have come from the CFI and **not** the SAP envelope. This year less than $0.5M of NSERC funding is being invested in particle physics equipment – all in the ATLAS trigger system and upgrades. An interesting question is whether we can ever again expect to fund the construction of a major piece of detector hardware from the SAP envelope given the other pressures it faces.

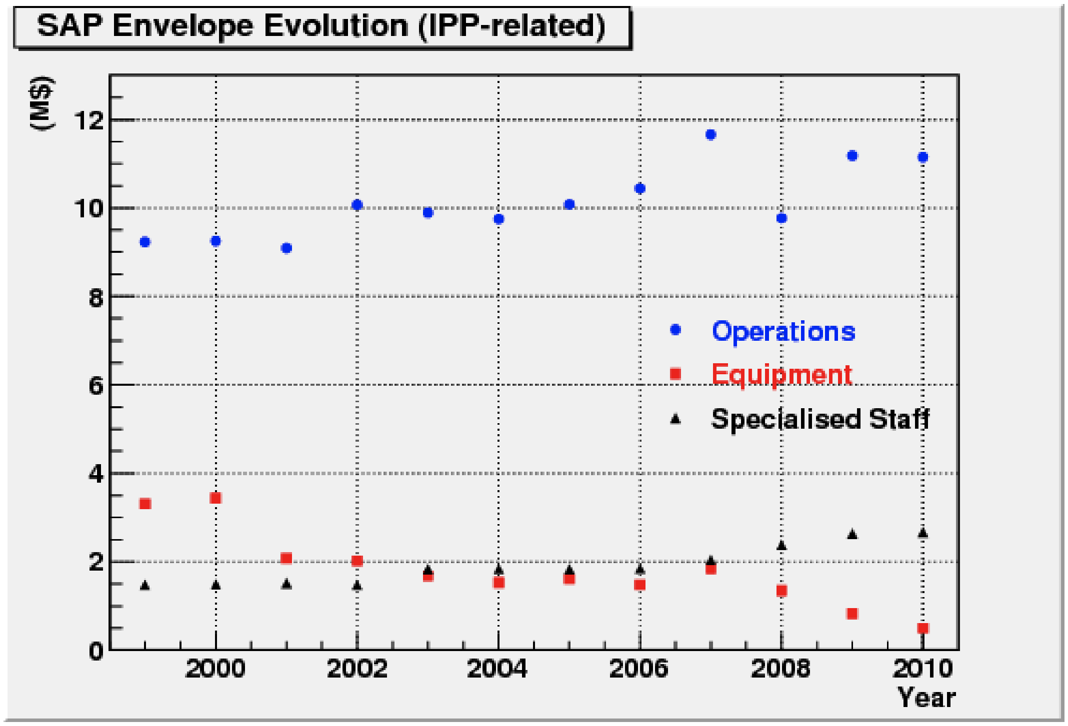

Figure 6: Funding for IPP (and IPP-related) projects from the NSERC SAP envelope over the last twelve years. The circles corresponding to project/operating grants, the squares to equipment grants and the triangles to MFA/MRS grants including the IPP grant itself. Theorists' Discovery Grants are not included here.

Finally one also sees a marked growth in the MRS/MFA component of the envelope. We believe this is another facet of the dramatic increase in research intensity that has resulted from the faculty renewal we have experienced. While we have been able to secure funding outside the NSERC SAP envelope for our GRID computing installations the specialised personnel to make them useful for the research community have spurred the recent increases in MRS support. Similarly the technical personnel necessary to make the detector developments necessary for the current and future generations of experiments have continued to grow. This is especially true as we have taken on more projects: three or more SNOLAB experiments as opposed to just SNO; and four or five accelerator-based experiments in various stages of their life-cycle (BaBar and CDF upgrades, ATLAS and T2K construction, ILC prototypes and R&D). Finally, as the experiments we're involved in have grown significantly we rely ever more heavily on the IPP scientists to anchor our efforts at the international labs. Five of the IPP scientists are involved in ATLAS, with two spending significant fractions of their time in Geneva, while three IPP scientists are involved in T2K, with at least one spending a term in residence in Japan. Once again, this is a reflection of the importance these scientists and the role they play ensuring the significantly increased number of students and postdocs on our projects are optimally engaged in the large scientific enterprises that have become the norm in our field.

As noted above there have been several significant shifts in the way the GSCs and Evaluation Section have chosen to deploy the SAP envelope's resources over the last five years. While external forces have influenced the grant requests submitted and thus circumscribed the response of the peer reviewers, it can't be long before someone asks whether we really need an SAP envelope whose main raison-d'être was to allow us to manage long-term fluctuations between the domains of operating, capital and support of specialised personnel. The IPP believes this LRP must make a strong case for the continued existence of the envelope and suggests that additional measures be put in place to ensure large capital expenditures on detector apparatus remain possible – given proper foresight and a credible scientific case. Explicit funding mechanisms that allow the community to argue for long-term strategic funding decisions should be considered, akin to the forward borrowing/banking that has occurred in the last decade, but on a less ad-hoc basis. Perhaps NSERC would consider an explicit stage in the SAPES deliberations where the peer-reviewers would consider formal submissions from the community with multi-year funding outlooks assessing the opportunity costs of funding a small scale project now vs. saving a few $M in order to undertake a larger project a few years down the road. Failing this, the LRPC should comment what the envelope should look like in the absence of a capital component, and advise NSERC accordingly, before they decide to re-structure the SAPES envelope away entirely.

A fundamental limitation exacerbating the strain on the SAP envelope is the fact that the size of the envelope has not kept up even with the growth in the number of grant-eligible researchers in the community, much less with the significant growth in HQP in the Canadian community. As was shown in Section 5.1.2 (see Table 2), in the last year alone the number of researchers in Canada doing particle physics has grown by about 10%, while graduate student and postdoc/RA totals exceed 20%. The SAP envelope itself has not grown accordingly, and the resulting effects on the use of the envelope as illustrated in Figure 6 are thus understandable. We place extremely high priority on increasing the absolute size of the SAP envelope in proportion to the growth of the number of grant-eligible researchers working in subatomic physics in Canada. Sooner or later this kind of pressure will discourage the top-flight researchers we've been able to attract to Canada through the CRC program and the availability of CFI-funded infrastructure. Eventually this could undermine the government's vaunted goal, evidenced by the introduction of the CERC University chairs and the Vanier post-graduate scholarships, of making Canada the best place in the world to do fundamental research. Ultimately this could initiate another brain-drain.

6.3 The CFI: A sole source of capital funding?

Over the last decade the CFI has made significant, crucial contributions to the funding of scientific infrastructure for subatomic physics in Canada as outlined in section 6.2. As highlighted in the last SAP LRP over \$75M of capital funding, more than half of which was provided to construct SNOLAB, came into our field through 2005. This process has continued with \$15M of CFI support [§] for the Canadian LHC Tier 1 computing centre at TRIUMF, \$21M of support for SNO+ and DEAP and, perhaps less directly connected to particle physics, the \$36M recently awarded to support the construction of eLINAC at TRIUMF, based on ILC-inspired superconducting RF cavities. In addition there have been a larger number of smaller CFI awards for new faculty that amount to an additional \$5.2M. Suffice to say that without the CFI the Canadian particle physics landscape would be much bleaker today.

As we are all aware these capital infusions have placed tremendous stress on operating support, requiring GRID computing specialists to make the computing equipment useful to HEP researchers, or specialised SNOLAB staff to make the underground laboratory space accessible to researchers in our community. At the same time, while all the projects that have been funded in this way have been highly deserving, funding has often been driven more by regional and institutional CFI quotas than the national and international vision that underpins the scientific ambitions of our community. Long-range planning committees and the community itself have sometimes been presented with projects funded through CFI as a fait-accompli and asked to respond after the fact. While the ability to coordinate the planning of capital support between NSERC and the CFI may be beyond the scope of the LRP exercise, communicating the importance of the synergy between the different funding sources and the long-term nature of the projects we undertake to the CFI remains one of the highest priorities of the IPP. Whatever the LRP can do to support us in these efforts would be most welcome.

Perhaps the largest challenge looming on the horizon, in this context, is the prospect of making a significant capital contribution to an off-shore particle physics experiment. This could be a significant capital investment in a SuperB drift chamber or a next-phase long-baseline neutrino experiment (perhaps a few \$M) or a major contribution to the upgraded ATLAS experiment – currently imagined to be something like 1/4 of the cost of the original ATLAS detector, meaning the Canadian share of this could be \$4-\$5M – all the way to the construction of a detector system for the next lepton collider that might cost twice that of an LHC experiment, thus making the Canadian share in excess of \$30M. While the CFI held one “international” competition with simplified matching fund requirements, it turns out that 4 of the 8 projects funded (SNOLAB, Neptune, the Arctic Ice Breaker and part of the Canadian Light Source) have all been in the headlines as much for the challenges they faced to secure subsequent operating funding as for the science they have done. One additional project that was funded in that competition – K0Pi0 – was eventually canceled by the international host. This is not an easy backdrop against which to argue for more competitions of this type. Still these challenges only serve to highlight the importance of community planning exercises and an over-arching strategic vision being an important ingredient in decisions to fund projects of this nature. The IPP has engaged the CFI administration with some success over the last few years. It remains to be seen how the new leadership at the CFI will approach this file.

The last SAP LRP felt that we should be ear-marking \$4M per year for new projects even in the status-quo funding scenario (note this is higher than the levels seen at the beginning of the last decade, cf. Fig. 6) and contemplating \$10M per annum capital investments in more optimistic funding scenarios. To some extent we find ourselves in these more optimistic scenarios, thanks to the CFI awards noted at

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[§] All “CFI support” quoted in this document **includes** the associated matching funds from provincial partner agencies and others.

the beginning of this section. Still, we emphasise that these investments are not the result of a deliberate strategy to optimise Canadian investments in a particular field of science. In a field like ours, where there are likely to be only a handful of very large projects going forward in the years ahead we need to anticipate the direction of the field and make strategic, deliberate and reliable investments if we are to maintain our preferred partner standing. The IPP urges the LRP to emphasise the unique and collaborative nature of capital investments in our field – we're not going to build an ATLAS or T2K by ourselves and 'out-do' the international competition. We need to continue to bring our share of the resources (both human and capital) to these projects, to stand side-by-side with the our international peers at these global facilities in order to assert our leadership in the discoveries they will make.

6.4 The MRS program

The support of research support staff has been facilitated by NSERC MRS awards (formerly MFA's). The funding provided support for staff in the areas of detector development and machine shop personnel as well as computer support for users, system administration and application support. The awards were made (in most cases) to a single university group and shared across projects as the latter evolve over many years or decades. The allocation of MRS awards has favoured institutions with a record of success in obtaining such awards (often related to an accelerator facility that was operational decades ago); new groups have found it difficult to get funding despite strong arguments.

In addition, to the support of university groups, the MRS program has supported the Institute of Particle Physics and HEPNET/Canada. HEPNET/Canada has been funded since 1994 and is responsible for national and international network connectivity for the subatomic physics community. Although HEPNET/Canada has been typically funded through one university (initially Carleton and now Victoria), it provides community-wide support and has been considered a success. More recently, ATLAS-Canada was awarded an MRS to fund its Tier 2 computing support staff together with the Compute Canada MRS.

NSERC has evolved the terms of the MRS awards requiring multi-institutional teams with a more focused (in some cases even project-specific) goal. This is a significant shift that is in the process of radically changing the support of the particle physics community. For example, staff for detector development are required by a project in its early phases and then again for upgrades. In the previous model, the staff at a single university could be shared between multiple projects which have different time-lines; this makes more effective use of the staff. The shift to multi-institutional, project-oriented MRS awards is hence problematic: detector development is very difficult to do remotely and sharing resources in this way is likely to be inefficient. It is also difficult to find term staff with required expertise; particle physics detectors are developed over many years and it is important to keep such staff in long-term positions.

Further, software and computing system in particle physics are getting very complex requiring significant expertise. It may be possible, in some instances such as the ATLAS-Canada Tier 2's, to have a common MRS application. However, it is already leading to complications at some institutions where there are other projects (in addition to ATLAS) where computing support is required.

The IPP recommends that a review of the MRS program for particle physics be undertaken to address the shortcomings we've identified above. Such a review could make recommendations on project or institutional MRS awards and how they can be used to provide the structural support that is key to the success of the particle physics community. We comment more on this in section 8.2 below.

6.5 TRIUMF support for particle physics

TRIUMF has traditionally played a critical role in supporting particle physics projects in Canada, particularly in the area of detector design and construction. Over the last two decades the Canadian ATLAS, BaBar, and T2K groups have all been heavy users of TRIUMF resources for detector and sometimes beamline contributions to their respective projects. For example, the BaBar drift chamber was built at TRIUMF even though no TRIUMF scientists were members of BaBar. The ATLAS hadronic endcap calorimeter production relied heavily on TRIUMF infrastructure and staff support while the ATLAS signal feedthroughs were produced at Victoria with significant contributions from TRIUMF staff based there. The T2K tracker modules (three time-projection chambers and two fine-grained detectors) were similarly designed, built, and tested at TRIUMF before being deployed to Japan. In this case a large T2K group centered at TRIUMF served as a focal point for these contributions. TRIUMF's core operations are supported by five-year Contribution Agreements through the National Research Council. One of TRIUMF's mandates has traditionally been to support the Canadian particle physics community. It would therefore be natural to expect TRIUMF to play a central role in future large particle physics projects in Canada, as it provides a critical mass of designers, engineers, detector physicists, and facilities to support large-scale detector projects.

However, the level of federal funding provided to TRIUMF for its 2010-2015 operating plan has placed the lab in a very constrained financial situation. The next five years of "flat funding", at the same level as the previous five years, amounts to an effective cut in funding in real dollar terms, and with it the lab must restrict its activities. While externally funded projects such as ARIEL (now funded) and UCN bring in money and allow TRIUMF to extend its program, these projects place additional demands on TRIUMF staff, since the lab must commit sufficient manpower to these projects to ensure their success. These new commitments, coupled with TRIUMF's need to reduce its overall salary budget by $\sim 10\%$, place sharp limits on (it may not be too strong to say "eliminate") TRIUMF's ability to provide support for new particle physics initiatives.

At present it does not seem realistic to expect TRIUMF to support major detector contributions to new projects over the next five years. For example, while TRIUMF is currently providing some support for prototyping work by the SuperB group, resources do not seem to be available to support a detector contribution to SuperB of the order of the Canadian detector contribution to BaBar. Should SuperB go forward in Italy with Canadian participation, the Canadian contingent will need to find a way of making a contribution that does not rely on significant time, talent or resources from TRIUMF. This mode of operation, while possible in principle, has not happened since the construction of the Canadian calorimeters for ZEUS, that were produced in rented facilities by term-limited staff. Once those calorimeters were delivered all of this infrastructure and expertise was lost to our field. Ultimately TRIUMF's tight funding constraints may limit the size or form of Canadian participation in SuperB. This is merely one example of a more general problem, in that other potential new projects, are unlikely to leverage TRIUMF resources either.

TRIUMF's current activities in particle physics include continued support for ATLAS and T2K, particularly serving as analysis centres, targeted contributions to particular SNOLAB projects, especially DEAP and SNO+, and completion of the PiENu rare meson decay program. Activities on UCN and ARIEL are now beginning to ramp up. Future support for the SFU-led Tier1 data centre at TRIUMF is also a critical issue. At present these resources are necessary to meet Canada's obligations to international agreements with CERN.

These contributions are critical to their respective projects and have not yet been impacted by the current budget situation, but it is not known how secure these efforts are in the longer term. In general, however, the best that can be hoped for in the next five years are for existing TRIUMF efforts in experimental particle physics to continue at their current level or with modest decreases, while support for new initiatives seem unlikely to be available. The IPP highlights this natural tension but urges the LRPC not to over-estimate the lab's ability to underwrite the production of particle physics detector systems to the extent is has been able to in the past. An increase in TRIUMF's operating budget in its next five-year plan is critical for the long-term health of the particle physics community in Canada.

6.6 Canadian collaboration with CERN

Canadian subatomic physicists have a long history of collaboration with CERN, extending beyond particle physics to include experiments at ISOLDE and the anti-hydrogen experiment, ALPHA. Our first major collaborative project, the OPAL experiment at LEP included upwards of 20 grant eligible physicists and produced over 47 PhDs during the 1990s and early 2000s. In the early 1990s Canadians played a leading role in the founding of the ATLAS experiment and TRIUMF made crucial, in-kind contributions to the LHC accelerator complex. Today CERN counts 150 registered users from Canadian institutions, we have 43 grant eligible researchers working on the ATLAS experiment, over 1/3 of our experimental particle physics community. With the excitement surrounding the prospects for discovery at the LHC a significant fraction of the Canadian particle theory community is also centering its research focus on CERN, including a growing contingent from the Perimeter Institute.

During the construction of the LHC CERN established cooperation agreements with various international partners. The Japanese, Americans and Indians all accepted observer status on CERN council in exchange for their contributions to the accelerator and experiments. In 1995, Canadian researchers identified and funded LHC contributions earlier than these countries. Upon completion of the LHC Canada's contributions to the PS quadrupoles, LHC beam cleaning insertions and injection kickers amounted to \$40M, while our contributions to the ATLAS experiment exceeded \$14M. Per capita, these contributions ended up being as large as any of the observer countries. Despite serious negotiations in the late 1990s Canada chose not to sign an agreement to be an observer on CERN council and these contributions were made under the auspices of an MOU between CERN and TRIUMF. Today Canada is by far (a factor of three) the largest non-member, non-observer contingent at CERN.

Looking forward to building support for its next big high energy physics project – whether this is an upgrade to the LHC or a major stake in a linear electron positron collider – CERN has recently concluded an examination of its role in European and world-wide high energy physics. CERN Council struck a subcommittee to examine possible geographic enlargement as well as its potential role in the governance of global projects. While it is imperative that high energy physics maintain cutting edge facilities around the world, it is clear that CERN will be the focus of energy-frontier physics for at least the next decade. Researchers are flocking to join LHC experiments and/or collaborate closely with the European theory community. The ICFA model, that states international research facilities should be open to all collaborators subject only to the peer review necessary to ensure their scientific credibility, is under strain. This model's basic tenet is that researchers from other countries/regions should have access to world-wide facilities without having to pay for their operation, based on the assumption that major HEP partner countries will pay to operate their own facilities and make those free to researchers from other countries on an informally quid-pro-quo basis. With the closure of the *B* factory and the imminent shutdown of the Tevatron major international participation in US laboratories will be curtailed in the coming decade. While Canada operates SNOLAB and TRIUMF that have non-negligible participation from the international community it is probably true that there is an imbalance, with almost twice as many Canadian researchers working abroad relative to those we host at Canadian facilities.

With this background the CERN committee on geographic enlargement has proposed a new associate member status at CERN. Associate members would have representation on Council, access to CERN training programs, including scientific fellowships and access to tender for CERN commercial contracts. CERN is currently funded as a fraction of the GDP of its full member countries. With an annual budget slight in excess of 10^9 CHF the Spanish contribution (a country with a GDP comparable to Canada's) is 90 MCHF/year. While the role in CERN governance would be limited, relative to the full member countries, it would be the same for all associate members. The current proposal is that associate member countries would make a contribution that would be 1/10th of that of full members countries. This would be about $9M/year for Canada. Access to commercial contracts, training programs etc. would be proportional to the financial contributions made by each country.

The most visible benefit of Canada becoming an associate member would be to normalise our relations with CERN giving us much better credit for our contributions to the scientific and technological breakthroughs produced at CERN [¶]. However, the strongest argument for establishing a formal relationship with CERN would be the direct benefits to Canadian industry. About 40% of the CERN budget ends up in commercial contracts for scientific infrastructure needed to operate the accelerator and detector complex. While TRIUMF and SNOLAB do very well in engaging domestic industry to produce cutting edge scientific instruments, access to CERN commercial contracts would provide an international arena where Canadian industry could demonstrate its capabilities and prove itself against the best in the world. The Canadian Space Agency has a 30+ year agreement with the European space agency that provides our aerospace industry with access to international contracts, beyond just those of NASA. Our colleagues in Astronomy have built strong working relationships with domestic industry in the development of telescope domes and other cutting edge astronomical equipment. The visibility that would be provided by, just a few Canadian companies, winning bids on future pieces of CERN infrastructure could be instrumental in expanding their international market and cementing the role of Canadian subatomic physics in the fostering of domestic industry.

Finally, while Canadians currently enjoy free access to the CERN scientific infrastructure, along the ICFA guidelines, the rapid growth of our community working there and the increasing constraints on CERN's infrastructure are making this situation less and less tenable. While we continue to be valued for our intellectual contributions [‖] the time when CERN might have to re-consider its open access policy may not be so far off. It would be short-sighted not to engage CERN, at this relatively modest level. Canada is in a unique position to play a leadership role in international scientific cooperation by establishing an existence proof for the associate membership status with CERN. The benefits to Canadian industry and the opportunities for Canadian researchers to train with the best of their peers would be an added benefit.

Even the CERN geographic enlargement committee only sees this as a stepping stone towards establishing a viable model for the governance of truly global scientific projects. High energy physics is unique in that the scale of our current projects are an order of magnitude larger than most ground-based endeavours and our aspirations are as large as any scientific projects currently underway (ITER, the ISS, Hubble,

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[¶] For example all CERN press-releases include a footnote that list the 20 member countries and seven observers. Canada is mentioned nowhere despite the fact that our involvement exceeds that of several member states and four of the seven observers. In CERN's mind Canada often ends up being lumped together scientifically and technologically, with China (not so bad) and Pakistan (less impressive).

[‖] The CERN experiments currently count more than 40% of their collaborators from non-member countries, so they could not function without the participation of researchers working for non-European laboratories.

etc.). The LHC was only realised thanks to a truly international partnership of CERN, its observers and other non-member partners (like Canada) cobbled together in an ad-hoc way. If a linear electron positron collider is to be built our field needs to lead the way in establishing a more broadly-based international partnerships.

Canadian associate membership is an important first step in this process. The IPP supports efforts to proceed with these negotiations, but recognises that this is a financial step that **cannot** be taken within the context of the NSERC SAP envelope. This is another example of a major science portfolio that has not been fully appreciated by policy makers in Canada. Just as SNOLAB operations would cripple our ability to mount experiments and train the next generation of innovative scientists, if it were to be taken from the SAP envelope, this is another case where the true costs of our research will eventually need to be acknowledged. We can only proceed if there were both policy and financial support from beyond NSERC, with explicit understanding that such funding cannot replace any component of our existing programme.

6.7 Summary of structural issues

While it is clear that many of the structural issues addressed in this section can most easily be addressed with additional funding, several of them could be alleviated with better coordination between existing programs or a better balance between the various components of any MIST program: capital, operations, researcher support and support for students. What is much less clear is how much additional funding might be necessary and where this *should* come from. In many cases these are not issues that can be addressed with the NSERC-SAP envelope, however they all serve to leverage, or de-leverage the research support NSERC provides Canadian researchers. In addition, the structural issues raised here have appeared, or are appearing, on different time-scales.

The SNOLAB operating funding situation has been with us for more than five years and a solution hasn't been found. Every year the SAPES is presented with a smaller or larger request for SNOLAB operations support that has the potential to significantly skew the remainder of the grants competition. While, up to now, other funding sources have been found – often **after** the SAPES competition – finding an enduring solution to this challenge remains the particle physics community's highest priority as it is also a test case for the support of major science infrastructure in Canada. Operating support for the Tier1 centre at TRIUMF ranks a close second, as it has the potential to undermine the lab's ability to support other core activities in particle physics. The resolution of these two issues will have ramifications on all of the other challenges we have raised in this section.

Beyond this, NSERC support for operating grants and MRS personnel commensurate with the increase in research intensity of the particle physics community in Canada, healthy support for TRIUMF as it underpins our community's ability to provide cutting-edge contributions to experiments around the world, and an ability to engage with international partners such as CERN, while involving Canadian industry, are equally important. We rank these together as next on our list to be addressed. These three structural issues may resonate with different government stake-holders. The funding sources are likely to end up being very different. As it is not clear that they compete directly with each other for funding the IPP feels they should be pursued independently. Missing out on any one of them could seriously undermine our community's position as a preferred partner in particle physics projects in the future.

7 Scientific priorities for particle physics in Canada

Prioritisation among the ongoing and proposed particle physics projects in Canada is a difficult process that must take into account several often contradictory criteria:

- Scientific motivation and potential for discoveries;
- Existing support within and investment from the Canadian particle physics community;
- Potential to increase the stature and profile of particle physics in Canada;
- Cost;
- Breadth of programme;
- Ability of Canada to make a significant contribution.

To the extent that any single factor must drive the prioritisation, scientific motivation must be given the highest weighting, and yet sociological and practical considerations must be taken into account. Here we divide sixteen ongoing and proposed projects into four categories:

1. Essential projects: those that must be fully supported under any scenario;
2. Potentially essential projects: highly recommended projects that currently lack one quality that prevents them from being placed into the essential category, but that have the potential of becoming so over the next five years;
3. Highly recommended projects: those with strong scientific merit and the potential for a significant Canadian contribution that should be supported if possible;
4. Projects of lesser priority: those that lack either strong scientific motivation or the potential for a significant Canadian impact.

Within each category the projects are listed alphabetically. Thus no ranking within in the categories is implied. These rankings do not map simply to funding levels. For example, a smaller project in the second category might receive less funding in absolute terms than a larger project from the third category, but might receive more funding relative to its FTE involvement.

7.1 Essential projects

Four projects receive the highest ranking, and must receive strong support for us to reap the physics benefits that we re-affirm are still of paramount importance to the Canadian particle physics program.

ATLAS: The large investment and involvement of the Canadian particle physics community and the potentially immense possibilities for discoveries that could reshape all of particle physics mandate that ATLAS receive the highest possible ranking.

DEAP: DEAP is a Canadian-led core effort of the SNOLAB programme in dark matter searches. While the DEAP approach has received less attention than two-phase noble gas detectors and germanium detectors, it has significant existing support within the Canadian underground science community, and as a cornerstone of the SNOLAB programme should be supported.

SNO+: With a diverse programme of searches for neutrinoless double-beta, measurements of solar and reactor neutrinos, and, with luck, supernova physics, SNO+ leverages Canada's previous investments in SNO, contributes to several key questions in neutrino physics, and has a critical mass of support in the Canadian community.

T2K: Canada is one of the largest contributors to the T2K experiment, and played the critical role in building T2K's near detector. Canadians hold a disproportionately large number of leadership roles within T2K, and are poised to dominate the area of long baseline neutrinos. The combination of worldwide interest, previous Canadian investments, and potential for leading analysis contributions makes continued support for T2K in Canada essential.

7.2 Potentially essential projects

Four projects have the potential to become essential projects over the next five years. They should all receive robust funding. Each currently lacks one key element that is needed to make them essential to the Canadian particle physics program. In addition, promotion of any of these projects to the essential category raises concerns about our community's size and our ability to find a critical mass of researcher-effort to provide the Canadian leadership we would expect from **all** our essential projects. Should the missing ingredients be fulfilled for one or more of these projects they should then receive support on a par with our most highly ranked projects.

EXO: EXO is one of the most promising approaches in the search for neutrinoless double-beta decay, with the potential of becoming a background-free measurement if barium tagging can be accomplished. The Canadian group has emphasised the capacity of a gaseous detector for improved background rejection and/or measurement of angular correlations between the decay products. While the Canadian membership in EXO is still modest in size, a decision by the collaboration to either move towards a gaseous detector or to relocate to SNOLAB would likely push this project into the "essential" category.

PICASSO: PICASSO may be considered a pioneering dark matter experiment with a long history of Canadian leadership and complementarity to other technologies for direct dark matter searches. A significant improvement in background reduction using recently observed alpha/neutron event-by-event discrimination and improved purification techniques will be necessary for PICASSO to remain competitive in the longer term with other techniques. However continued support to explore these potential improvements is highly recommended.

SuperB: The tremendous success and high profile of Canada's contributions to BaBar warrant support for a contribution to a next-generation experiment at Frascati. Funding of the project in the host country is still not secure however, and SuperB, as a potentially large detector project, may be especially impacted by TRIUMF's limited ability to support new hardware initiatives from the Canadian particle physics community. This is one area in which an increase in funds available through the NSERC SAP envelope or through CFI support for an off-shore detector contribution could pay large dividends.

Super-CDMS: CDMS has led the competitive field of direct dark matter detection for nearly a decade, and is consistently ranked by international review committees as the highest priority experiment within the dark matter community. Super-CDMS's plans to relocate to SNOLAB received international media coverage and placed a spotlight on Canadian particle physics. The relatively small size of Canadian participation in Super-CDMS mitigates against an even higher ranking, although if more Canadians join the effort this could change.

7.3 Highly recommended projects

These projects, while having potential to impact particle physics in the coming decade, are viewed as less central to the Canadian program. As many of these projects should be supported as resources allow.

International Linear Collider (ILC): Assuming that LHC finds evidence for new physics, as is widely anticipated, a high-energy linear collider would have unparalleled scientific motivation. This, plus the existence of a core group of Canadian researchers with high interest and relevant experience, warrants that Canada keep the door open to significant involvement in the ILC. Mitigating against a higher ranking is the still uncertain timescale and scope of the ILC and the likelihood that it will not move into the construction phase within the scope of the current planning period.

VERITAS: The modest Canadian involvement in VERITAS has contributed to a successful series of high-profile results within the gamma-ray astronomy community. Continued support to allow the Canadian members to contribute to the duration of VERITAS's analysis and data collection programme is recommended, although at present we cannot place the same priority on Canadian involvement in future gamma-ray initiatives.

7.4 Projects of lesser priority

While we recognise that each of the projects ranked here could make important contributions to our understanding of particle physics we do not find the community support for them compelling and thus can't rank them more highly. Support for the following projects should not come at the expense of projects in the three higher-ranked categories.

BALCAL (dark energy): While dark energy has the strongest scientific case possible, and one can conceive of particle physicists playing a key role in many approaches to this question, the BALCAL effort is much closer to astronomy than any other project that has received support from the Subatomic Physics Evaluation Section, and its proponent should probably seek support from the Astronomy Evaluation Section.

IceCube: Although the particle physics case for IceCube is at least as strong as that for VERITAS, current Canadian involvement is limited to a single Canadian PI who is migrating his efforts to DEAP. We recommend sufficient support to allow this PI to conclude his involvement while transitioning to new projects (much as young collider physicists were supported to work on D0 in the past before switching to LHC).

J-PARC $g-2$: A proposal to contribute to a $g-2$ measurement at J-PARC is currently being studied for feasibility. It lacks a critical mass of dedicated Canadian involvement at present.

MoEDAL: The MoEDAL proposal to search for monopoles at the LHC is a scientific long shot. While the costs are modest, the low chance of finding monopoles means that the project should have a lower funding priority than those projects more likely to make an impact.

Rare decays: There does not seem to exist a sufficient critical mass of interest within Canada to warrant support for new efforts in the area of rare decay physics beyond the successful conclusion of the PiENu experiment, which we do support.

Ultra-Cold Neutrons: The proposed programme in ultra-cold neutrons can potentially address questions of relevance to particle physics, especially measurements of the neutron EDM, that provides strong complementary constraints on new physics such as SUSY. There is also benefit in supporting an on-site particle physics programme at TRIUMF. UCN does not yet have broad support from the Canadian particle physics community. There is concern that fulfilling commitments to UCN will limit TRIUMF's ability to support the high priority particle physics projects outlined above.

8 Amplifying Canadian leadership in particle physics

As we've outlined above the capacity of the particle physics community in Canada is sharply constrained by the available funding from the NSERC SAP envelope, which has seen little growth in recent years. In this section we highlight a few key areas which we feel are ripe for leverage, in that with increased funding disproportionate improvements to the health and vitality of the Canadian particle physics community would result. These may be thought of as "case studies" that argue for an increase in the envelope. No relative ranking should be inferred by the order in which they appear. In addition, they **should not** be seen as statements that we think projects should not be undertaken if no new funding were to become available. We thank the proponents of each project for helping with the preparation of the following sections.

8.1 Revitalising operating support for particle physics

As highlighted in the previous subatomic physics long range plan, pressure is continuing to increase on the operating component of the SAP envelope. A significant number of new, young, active and internationally acclaimed researchers, have been attracted to Canada by CRC chair positions and the promise of a modernised research infrastructure. This increase in new faculty (shown partly in Section 5.1.2 and Table 2, but also embodied in the 43 new researchers who started in the previous five-year period) has, not surprisingly, resulted in severe under-funding of operational support for particle physics researchers across the country, threatening to undermine these tremendous gains in human capital.

From Table 2 we see that an additional 25 RAs/PDFs and 50 graduate students have been hired over the last five years (discounting half of the Perimeter PDFs who are supported by non-NSERC/SAP funding). At \$60K per RA/PDF and \$25K per graduate student [**] this has required an additional \$2.75M in operating support over the last five years. Looking at Figure 6 we see that the reaction of the GSC/SAPES has been to increase operating levels by only \$1.5M over this same period. As a result, particle physics researchers must have found the difference (some \$1.25M) in efficiencies in their other operations, or injected this support from new-faculty startup support. Either way in the next five years we face the prospect of either finding another \$1.25M of operating support, or scaling back the significant advances we've made in HQP training in particle physics.

While the federal government has taken steps to increase the number of graduate student scholarships directly available to students it is clear that the rejuvenation of the faculty in particle physics has already increased the number of graduate students from 190 to 240, with a corresponding increase in research intensity and impact. In fact most of the younger faculty are already supervising two (or more) students each. We note that even two students per adviser is far below the five (or more) students per advisor that is typical in other areas of natural sciences and engineering where industrial support and targeted government funding are available. Further, we do not believe that this level of student participation is optimal, saturates the supervisory capacity of members of our community, or is dictated by the number of bright, young, students interested in pursuing graduate work in particle physics in Canada. The number of students involved is simply limited by operating support. An additional \$750K of would result in 30

[**] Both of these figures include salary, benefits where appropriate, and some minimal research/travel support associated with each of these positions.

new graduate student positions that would begin to address the gap between science potential, supervisory capacity and the number of students currently active in particle physics researchers Canada.

In experimental particle physics each graduate student's work typically results in the extraction of one additional physics result (and the corresponding publication) from the data. Theoretical graduate students typically produce three or four publications over the course of their time in graduate school. The physics output of RAs/PDFs varies, depending on the phase in the experiment's life-cycle, ranging from one publication during the construction/commissioning of an experiment over their few-year tenure as a postdoctoral researcher, to one (or more) publications per year in the active data-analysis phase. Similarly theoretical postdoctoral researchers produce one or two publications per year. Taking these inputs we estimate that growth in Canadian HQP has been responsible for an additional 70 publications over the last five years and, with the modest growth in numbers of students described above, could result in 170 additional publications in the coming five years. Such an increase in the number of areas Canadian researchers could explore would better leverage our existing investments and expertise at the scientific frontier. It will lead to a corresponding increase in the physics impact of our community.

These 170 projected additional publications correspond to the 25% increase in research intensity identified in Table 2 and discussed in section 5.1.2. We feel that the **$2M of additional operating support** (an increase of 13% over the current SAP support for particle physics of $15M/year) would be an ideal way to capitalise on the investments we have already made, increase the productivity and stature of Canadian researchers and train additional HQP, the majority of whom end up throughout Canada's innovation economy.

8.2 Refocusing the MRS programme for particle physics

Additional funds could be used to strengthen the capacities of the university groups by supporting technical staff in the areas of detector development and computing application through the NSERC MRS program. Currently the trend toward multi-institutional MRS awards can work for the large projects (such as the ATLAS Tier 2 computing personnel), however, it does **not** meet the needs of the smaller projects. In addition it un-reasonably constrains the use of these personnel in the exploration of new opportunities or new HEP detector or accelerator projects.

The MRS funds are required at a single institution and shared within the HEP groups (or other local groups). Single institute MRS awards, that were more prevalent in the era of the MFA awards, enabled the local groups to build and retain expertise in detector development. Often, this is the only opportunity for graduate students to get hands-on experience with detectors. Similarly, software application support can be project-based but not at the expense of the smaller projects. In many instances, one person can provide support for multiple projects and, as demonstrated by the BaBar collaboration, provide support to the smaller groups across Canada. The MRS support is becoming more important as TRIUMF is reducing its ability to provide assistance to the HEP community for the design, development and construction of detectors. Beyond the traditional uses the community had made of MRS-support the IPP, itself an MRS-funded organisation, has expanded its scope beyond just the support of research scientists, to include support for postdoctoral theorists, summer students at CERN and, very recently, high-school teacher opportunities to get involved in particle physics research. These HQP and outreach activities are also important for the health of our field and could be expanded in a less dire funding environment. New funds in the MRS component of the SAPES envelope would significantly benefit the community and enhance our ability to contribute to developing projects and the analysis of the data.

The IPP encourages the LRP to consider the current level of scientific, detector development and computing MRS support available to the community and assess an appropriate level of funding, but given the growth in size and research intensity in our community over the last five years we think doubling the support, relative to where it was in 2006 (at about \$2M) would be appropriate. **This would correspond to an increase of \$1.5M over the current levels.**

8.3 Upgrades to the ATLAS experiment

As discussed above, Canadians have been prominent collaborators in the ATLAS experiment. Over one third of the Canadian experimental community are members of ATLAS, and we have built, installed, commissioned and continue to maintain \$20M of the detector equipment in the experiment. While the LHC has started producing its first energy frontier collisions this year and the machine is continuing to ramp up to its design luminosity, plans are already being made for the second phase of LHC operations. Consolidation of the injector complex to ensure reliable operations up to the design luminosity of 10^{34} are already underway, and plans are already being made for what to do beyond the first five years of full intensity operation, that should yield 500 fb^{-1} of data. The implementation of these plans can only be triggered by initial observations from full-energy LHC collisions. If a suite of new SUSY particles are observed below 1 TeV then a luminosity upgrade would be required – to study the spectra of new particles in detail – while if nothing is seen out to 2 or 3 TeV then an energy upgrade might be required. While the former would be straight-forward for the machine with further upgrades to the injectors and LHC machine protection systems to allowing instantaneous luminosities up to 10^{35}, a ten-fold increase in instantaneous luminosity would require a major revamping of the detectors.

Upgrades to the ATLAS experiment are proceeding in stages. At this point a re-enforcement of the inner-most tracking layers is being proposed. The Insertible *B* Layer (IBL) is being designed to add a 4th layer of pixel sensors to the ATLAS inner tracking layer to ensure robust pattern recognition and *b* tagging up to the full LHC design luminosity. The \$10M IBL is currently being proposed for installation in 2016, when it is expected that the LHC will reach steady-state running at 10^{34}. Canadians are already playing an NSERC-supported leading role in the development of the radiation tolerant diamond sensors that are one option for this detector. If these sensors are chosen (the decision point is mid-2011) we would envisage a \$0.5-0.75M Canadian contribution to this upgrade. This might still be feasible within the scope of the NSERC SAP envelope.

However, beyond 2015, given sufficient evidence of new physics below the 1 TeV scale, ATLAS is contemplating more substantial upgrades to be able to cope with instantaneous luminosities that could increase to 10^{35}. These include a complete re-build of the inner tracker as well as modifications to the end-cap and forward calorimetry. In both cases a ten-fold increase in particle fluxes over the initial design of 10^{34} would render the existing detector systems inoperable. In the tracker the radiation dose would kill the inner solid-state layers and the occupancies would be un-manageable for the TRT. At larger rapidities the energy densities and currents in the liquid argon calorimeters would lead to high rates of recombination and large currents that would severely impair their performance.

Canadians are leading the efforts to study the limitations large energy densities will put on the operation of the forward calorimeters. Through a combination of operations of the existing detector, simulations and testbeams at very high particle fluxes we are working to understand how the detector performance will roll off at the highest luminosities, and indeed, to understand how far beyond 10^{34} the system might start to be compromised. In addition, NSERC SAP supported R&D is underway to study the radiation tolerance of a novel mini-FCAL that could be placed in-front of the existing cryo-stat to absorb 1/3 – 1/2 of the energy protecting the current FCAL even up to the highest luminosities foreseen at the LHC. The proposed system would use a series of diamond sampling layers to provide some energy measurement of this first part of the forward jet/showers, but requires linear charge response of diamonds up to doses of 10^{17}/cm^2 and beyond, a regime where diamonds have not been tested, until now. Work is already underway to measure the performance of diamond sensors in these fluence regimes at TRIUMF. Current estimates are that a diamond-instrumented mini-FCAL system – for both the forward and backward regions in ATLAS – could be built for $3M. These are sufficiently self-contained systems that it is hard to imagine how such a system could be built by many different institutes or in several different countries. Canada is naturally placed to provide this entire system for ATLAS.

Beyond the calorimetry, Canadians are also involved in plans to replace the entire tracker, should the physics warrant an increase in instantaneous luminosities up to 10^{35}. The diamond pixel sensor R&D, already underway for the the IBL replacement would have a natural follow-up in the full tracker replacement. The ATLAS tracker replacement design includes six layers of pixel sensors followed by 6 layers of silicon strips, filling the entire tracking volume. The three inner-most pixel layers would have to rely on a sensor technology significantly more radiation tolerant than traditional silicon sensors – such as diamond. In addition, the upgraded tracker will need a significantly more sophisticated readout in order to be able to cope with the order of magnitude increase in the number of charged particle hits and tracks. Through our involvement in the TRT readout system Canadians are well placed to play a role in the upgraded tracker DAQ system as well. The entire upgraded tracker is likely to cost $70-80M (about the cost of the current ATLAS tracker) despite the fact that it will have at least an order of magnitude more channels and modules. If diamond sensors were chosen for the inner layers of the upgraded ATLAS tracker, they would likely cost $9M. While Canadians would not be alone in procuring, testing and preparing these sensors we are likely talking about a $3M Canadian contribution to the ATLAS upgrade, with a similar contribution possible to the tracker DAQ. Other projects with strong Canadian interest are also being considered in the medium term, including contributions to the new calorimeter readout electronics and upgrades to the ATLAS level-1 trigger.

The timeline for ATLAS upgrades is such that it fits well with the current long range planning exercise. Data will be available by 2013 to provide the rationale for an LHC luminosity upgrade. R&D for the mini-FCAL and/or the use of diamond sensors in the IBL could have established the Canadian proposals as viable solutions for the upgrade. If the ATLAS upgrades are to be ready for data-taking before the end of this decade – a reasonable timescale for the baseline LHC to have delivered 500 fb^{-1} – construction will have to start in 2015. The IPP believes the ATLAS upgrades would make an ideal case for additional funding – both equipment and the support of the technical personnel needed to design and build parts of the tracker of the mini-FCAL discussed above – towards the end of the current planning period. As discussed above $4M/year in equipment funding is not out of line with past practices in SAP, but now seems difficult to imagine given the evolution of the SAP envelope. **The ATLAS upgrades would require $3M/year over three years between 2014 and 2016** if they were proceeding on the currently envisaged timescale.

8.4 Canadian involvement in SuperB

As highlighted earlier in this document Canadians have established themselves as leaders in the area of quark flavour physics with high profile contributions to the BaBar experiment as well as important contributions to other efforts at CDF, D0, CLEO and, further in the past, OPAL. While Canadians are well positioned to play an important role in the physics of the SuperB experiment, a contribution to the experimental apparatus is a pre-requisite to our continued leadership. As discussed above, the SAP envelope is under significant pressure to support the researchers and their students and postdocs on SuperB, just as any other experiment. While the CFI is one possible source of capital funding they have not, traditionally, funded equipment to be installed off-shore. Thus we believe that building, installing and commissioning a drift-chamber for the SuperB experiment is a good example of a project that with demonstrated Canadian capability that would significantly enhance our leadership in the international particle physics community disproportionally to the level of funding involved.

In the absence of capital funding beyond the current NSERC SAP envelope, the Canadian contribution to SuperB drift chamber construction will focus on items that do not require extensive capital. Examples include:

- slow controls, monitoring, alarm system
- high voltage system (modules, crates, cables, control system)
- trigger hardware and software
- gas system infrastructure (specifying gas shack, piping, safety system)

Other R&D related to construction is funded by the SuperB project grant, including:

- analysing backgrounds
- studying the feasibility and benefits of cluster counting
- developing a preamp suitable for cluster counting (wide bandwidth, low noise)
- overall conceptual design

Cluster counting dramatically increases the amount of information used in reconstructing the four-vectors of charged particles traversing the detector. In principle, this significantly improves the particle identification capability and the momentum resolution, thereby reducing the amount of luminosity required to reach benchmark physics goals. Cluster counting has yet to be implemented in any experiment, so such improvements need to be demonstrated in small prototypes before including it in SuperB.

Cluster counting will substantially increase the amount and rate of information to be extracted and transferred by the front end electronics, and also significantly increase the complexity of the embedded feature-extraction algorithms. The additional expense of developing and building these electronics is not included in the baseline plan of approximately $4M Canadian for the drift chamber electronics. About 40% of the nominal cost is capital, while the remainder is labour, including engineering and other technical labor, but not physicist time. Implementing cluster counting is estimated to increase the cost by approximately 30%, or $1.2M. Given additional funding of this level - and given a successful outcome of the ongoing R&D on cluster counting - the Canadian group would take responsibility for needed changes to the front end electronics. This project is also directly applicable to Belle-II, if the group were to move in that direction as a result of Italian or US funding decisions.

A natural role the Canadian group could play in the construction of the SuperB drift chamber is the assembly and stringing of the chamber, as the group did for BaBar. This is an excellent match to the expertise and facilities of TRIUMF. The BaBar assembly effort was funded by a Major Installation Grant with extensive support from TRIUMF for salaries (including both regular TRIUMF employees and the stringers hired specifically for the job), engineering and design, and machining. Additional support came from startup funds and the MFA program.

The cost of assembling the chamber, excluding the stringing robots, is estimated to be $900K in materials and supplies, plus two man-years of engineering and design, and six man-years of labor. In the SuperB costing formalism the total is valued at $2.2M; **the actual cost in the Canadian system would be more like $1.6M**, depending on the charge-back rate for TRIUMF personnel. This project would be an excellent match to the experience and interests of the Canadian group, and would be a good way to retain the detector design and construction expertise present at TRIUMF.

8.5 Hosting the EXO experiment at SNOLAB

EXO is currently leading the world in showing the path to sensitivity to very low neutrino effective mass $m_{\beta\beta}$, and is on the verge of running the most sensitive 0ν double beta decay detector on the planet, EXO-200. Canadians have initiated and are leading the work on the electroluminescence-based gas EXO detector and have provided the seminal ideas and substantial support for a barium tag using ion extraction from the high pressure TPC. Since 2005 Canadians have contributed over $2M to EXO with NSERC RTI and Discovery grants. The work on the gas option follows from a decision by the whole collaboration. Support from outside Canada for this work is provided by the Stanford and Alabama groups in the form of infrastructure, equipment and manpower. A new clean room was built at Stanford for the barium extraction tests. It was completed in March 2010, and was equipped with the large vacuum chamber shortly thereafter. In June 2010, the cryogenic Xe pumps arrived. They will maintain the xenon flow through the orifice. Turbomolecular pumps and valves for this new installation were received at Carleton and sent to Stanford. The American groups support four half-time postdoctoral fellows to work on barium extraction from high pressure xenon and on the gas detector. Other examples of support for the gas detector from outside Canada include the construction of the xenon system and the development of a detailed Monte Carlo for background estimates and calibrations planning, both by the Alabama group, and support for the design of the electronics by the Stanford group. In terms of manpower and resources, EXO is determined to grow the collaboration for the construction and operation of Full EXO. Two groups from Germany and South Korea have recently joined the collaboration, and discussions continue with other groups.

The plan discussed in Section 4.3.2 shows that data will be available in the years 2012–2013 that will provide the rationale for the decision on the technology for the Full EXO detector (gas or liquid), and on its location. SNOLAB or DUSEL are the most likely sites as WIPP is not deep enough. A feasibility study for the gas detector will be produced in support of that process. So, a bid for the cryopit at SNOLAB, an ideal cavity for such a detector, could be made as early as 2012. At this time, competing experiments will also be taking data: ZEN, GERDA (Phase II), CUORE (0) and SNO+ (^{nat}Nd). The EXO collaboration realises that the design and construction of Full EXO must proceed in a timely manner to maintain its lead towards lower values of $m_{\beta\beta}$ and into the parameter space where the inverted hierarchy is excluded. Two scenarios are contemplated for Full EXO:

1. *conservative*: 1 T of enriched xenon and 5 years live time, with an estimated background of 0.7 events over this period; gives an upper limit in effective mass is about 20 meV (90% C.L.);
2. *aggressive*: 10 T of enriched xenon and 10 years live time, with a background of 0.5 events; the upper limit for this scenario is about 5 meV (90% C.L.).

The first major result from the search for $0\nu\beta\beta$ will likely be the exclusion of the inverted hierarchy. This requires a sensitivity below 10 meV, which only Full EXO can reach. The IPP believes that the development of Full EXO will make an ideal case for a increase in the level of funding (for equipment, operations and support for construction) in the second half of the current planning period. The estimated cost for the construction of the Full EXO detector is $50M, which does not include infrastructure. Should the collaboration decide to build the project at SNOLAB, the Canadians would provide the infrastructure, worth $20M that would be requested from the CFI. If Canadians were to truly lead this experiment they would be expected to provide half of the remaining funds, or **$15M, for the detector components themselves, that would traditionally have been sought from the NSERC-SAP envelope.** This would be especially true if other partners were procuring the enriched xenon. This scale of investment is not dissimilar to the investment GSC-19 made in producing the Tigress spectrometer. We expect the EXO detector would play a similar role, anchoring the SNOLAB experimental program in the decade ahead, that Tigress is playing in the current decade at TRIUMF.

Another possible scenario is that a signal is found in the 0ν channel by 2013, with probably low statistical significance. Assuming an effective mass of 390 meV and average nuclear matrix elements for xenon, 160 events are expected after two years running EXO-200, compared to 40 background events. Although a positive signal in EXO-200, no matter how strong, does not resolve the hierarchy, it would be a major step in establishing the Majorana nature of the neutrino, and the focus should be shifted quickly to measuring the angular correlation between the two electrons while accumulating more statistics. This will distinguish between possible processes underlying 0ν double beta decay and requires a gas detector with good tracking capabilities and good energy resolution. By 2013 the data from the XEP will provide the assessment of its suitability for angular correlation. The vertex identification is more difficult and will require the addition of a moderate magnetic field of about 400 G to separate the two electrons by momentum analysis along the $\beta\beta$ track. An early Monte Carlo simulation has produced encouraging results, although the lateral drift can be a limitation. In this scenario, the need for more isotope and/or a larger detector will remain, although the scope will likely be smaller than that of a multi-tonne detector.