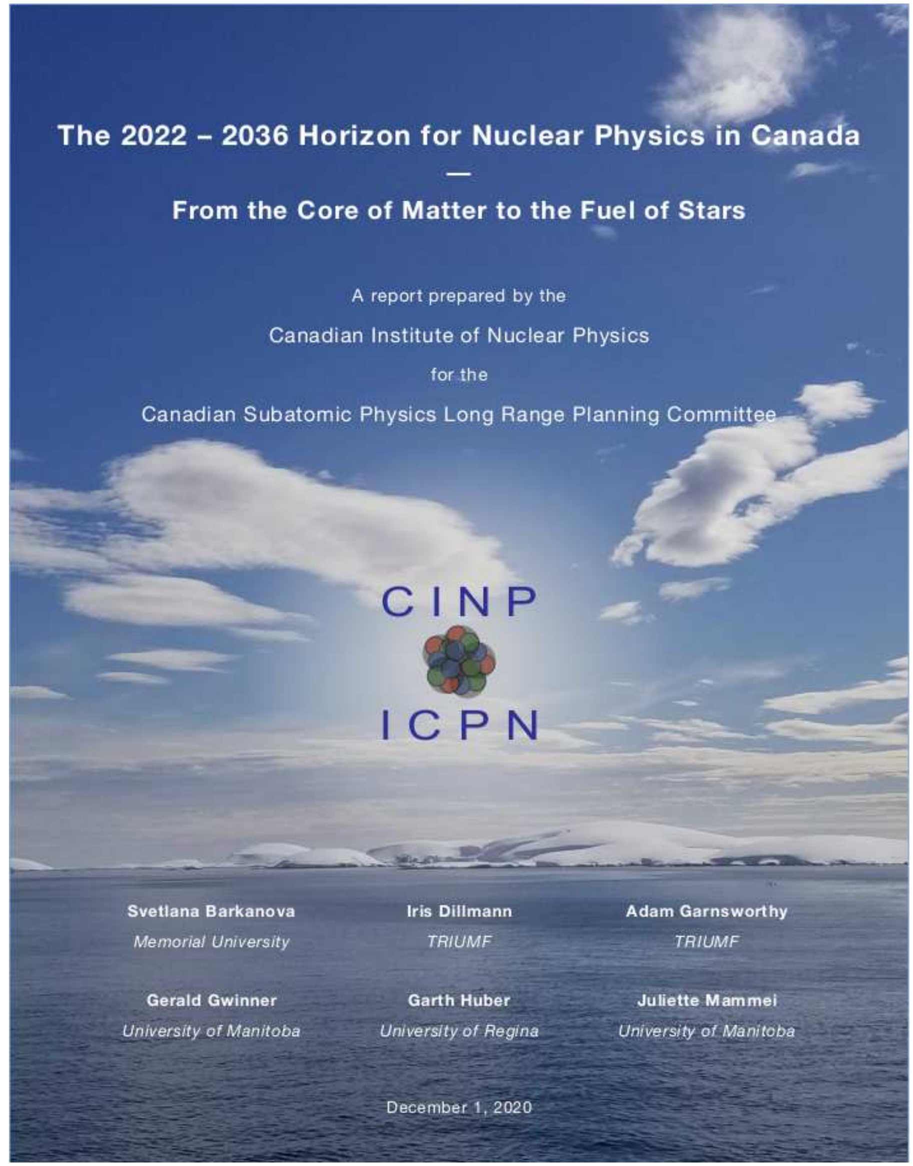
CINP
ICPN

Canadian Institute of Nuclear Physics

Institut canadien de physique nucléaire

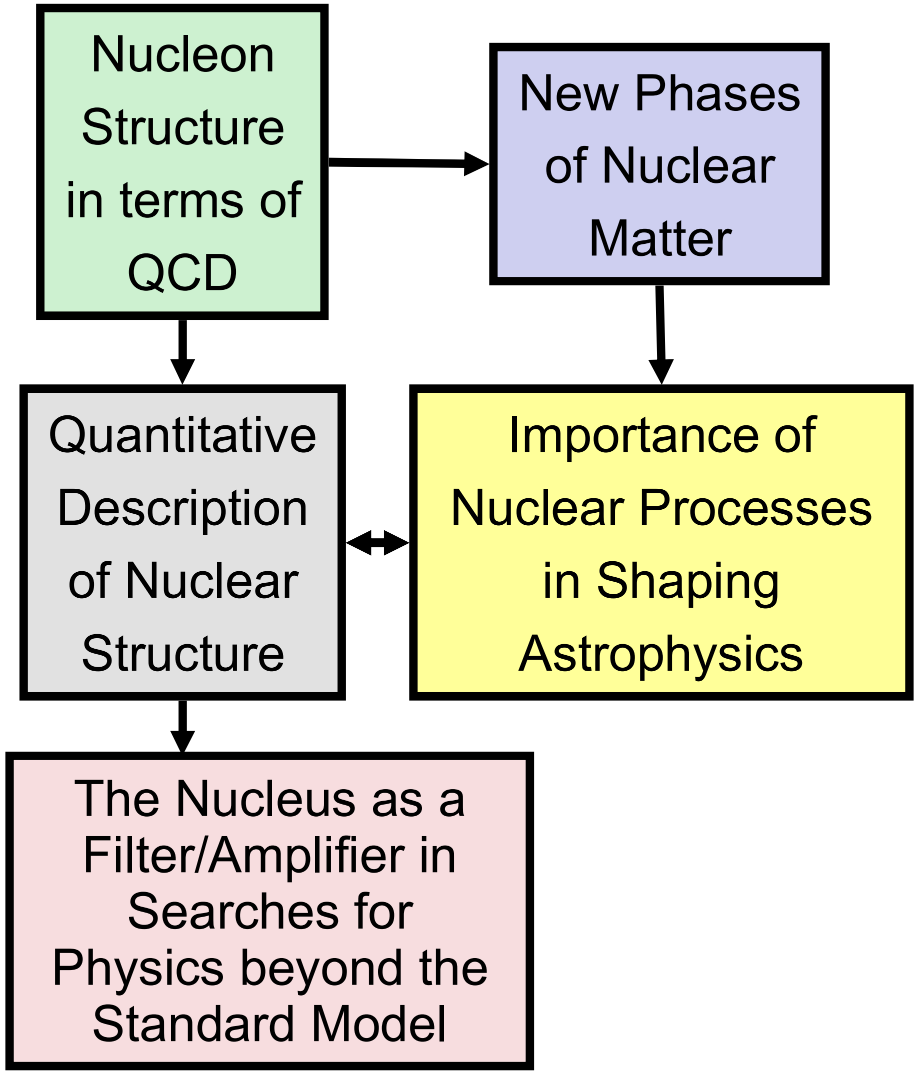


CINP White Paper Committee:
Svetlana Barkanova Memorial University
Iris Dillmann TRIUMF
Adam Garnsworthy TRIUMF
Gerald Gwinner University of Manitoba
Garth Huber University of Regina
Juliette Mammei University of Manitoba

Canadian SAP LRPC Town Hall Meeting **April 20, 2021**

Nuclear Physics is driven by fundamental investigations on the origin, evolution and structure of strongly interacting matter

- **Broad international consensus on the key questions of significance to the broader community**
- **Driven by the criteria of research excellence and critical mass of effort, Canadian nuclear physicists have *self-selected* their efforts to make substantive contributions to these "key questions"**



How do quarks and gluons give rise to the properties of strongly interacting particles?

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- We know that hadrons, strongly-interacting composite particles such as protons, neutrons and pions, are made up of quarks and gluons, but we only have partial answers on how quarks are distributed and moving inside.
- While the discovery of asymptotic freedom within the context of perturbative QCD was recognized by the 2004 Nobel Prize, we still do not have a complete solution in the confinement regime, where the quark coupling strength is too large to allow the use of perturbative methods.
- **The explanation for the observed properties of the hadrons remains one of the central problems of modern physics, requiring advances in both theory and experiment.**

How do quarks and gluons give rise to the properties of strongly interacting particles?

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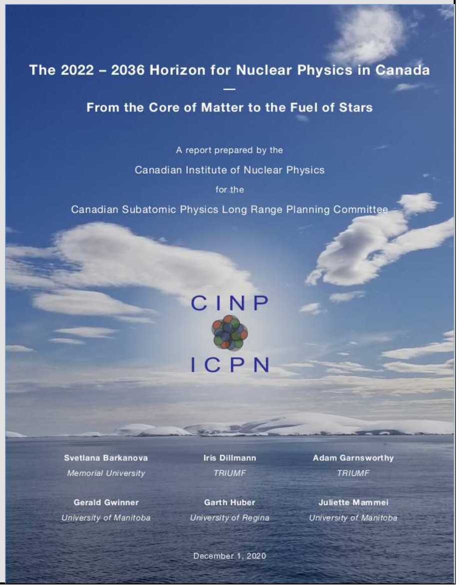
Canadians have made substantive detector contributions to the JLab 12 GeV Upgrade, and have moved to data collection and analysis mode.

- GlueX (exotic hybrid mesons) Hall D.
- Pion and Kaon Form Factors Hall C.

- <u>**Medium term (2022–26):**</u> Canadians involved in data taking and analysis of data. JLab Eta Factory (JEF) is planned with upgraded GlueX equipment for 2021–26.
- <u>**Longer term (2027-36):**</u> SoLID experiment at JLab
- Canadian participation at Electron–Ion Collider will uniquely address profound questions about nucleons, including the origin of hadronic mass, the origin of nucleon spin, and the emergent properties of dense systems of gluons.



What are the phases of strongly interacting matter, and what roles do they play in the cosmos?

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- At the highest densities, yet at still rather low temperatures, the quarks making up the nucleons of nuclear matter may form a new state of matter, which is color–superconducting.
- Colliding nuclei at relativistic energies also produces exotic matter when ‘nuclear temperatures’ reach values that represent a state of matter (the quark–gluon plasma) as it existed during the first moments after the Big Bang.
- **This question has significant bearing on our understanding of astrophysical phenomena such as neutron star structure and the evolution of the early universe.**

- **Canadian Program:** Relativistic Hydrodynamics

How does the structure of nuclei emerge from nuclear forces?

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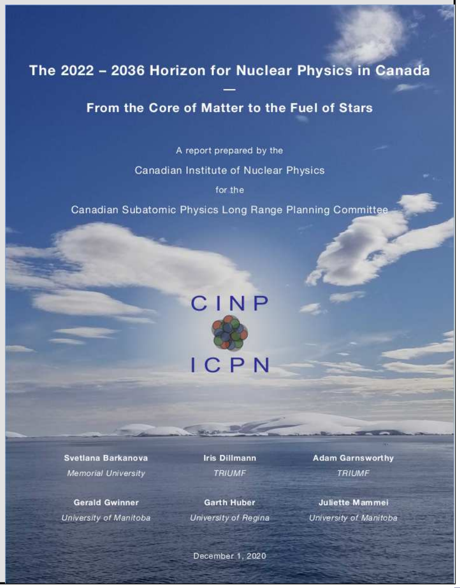
- A central pursuit of current nuclear structure research is to reveal the fine details of the strong nuclear force responsible for the properties of nuclei and nuclear matter.
- The rare isotopes are breaking the boundaries of our conventional knowledge and reforming our views on how nature organizes the building blocks, protons and neutrons, into a wide variety of complex atomic nuclei.
- Much to our surprise, we are now finding that the well-established nuclear shells disappear in rare isotopes while new ones appear.
- **While a few discoveries with light nuclei have opened a new paradigm, much of the rare isotopes remain unexplored.**

How does the structure of nuclei emerge from nuclear forces?

Medium term (2022–26): Highest priority is to capitalize on the recent investments in new world–class detector infrastructure at ISAC. New detector systems, such as EXACT-TPC and RCMP, will begin physics prgrams at ISAC.

Longer term (2027-36): ARIEL will be a next generation rare–isotope beam facility, new beam species, higher intensities, cleaner beams, longer beam periods.

- High quality work off–shore at GSI/FAIR, GANIL, RIKEN, FRIB, JLab
- Global ab–initio calculations of all nuclei may become possible in next 5-15 years, making statistical analyses of properties and limits of nuclei from first principles a reality.
- Nuclear structure investigations relevant to 0νββ may become a future direction.



What is the role of radioactive nuclei in shaping the visible matter?

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- August 17, 2017 detection of gravitational wave signal GW170817, followed about 1.7s later by a short γ–ray burst (GRB170817A), was identified as a merger of two neutron stars.
- This scenario is connected to the creation of about half of the elements heavier than iron in the "**rapid neutron capture (*r*) process**", and deeply connected to the nuclear physics of short-lived neutron-rich nuclei and the Equation of State (EoS) of neutron star matter.
- **Astrophysically important cross section measurements so far have been for nuclei close to stability, but this limitation will be overcome in the next decade and help push our understanding of the creation of the lightest up to the heaviest elements further than ever before.**

What is the role of radioactive nuclei in shaping the visible matter in the universe?

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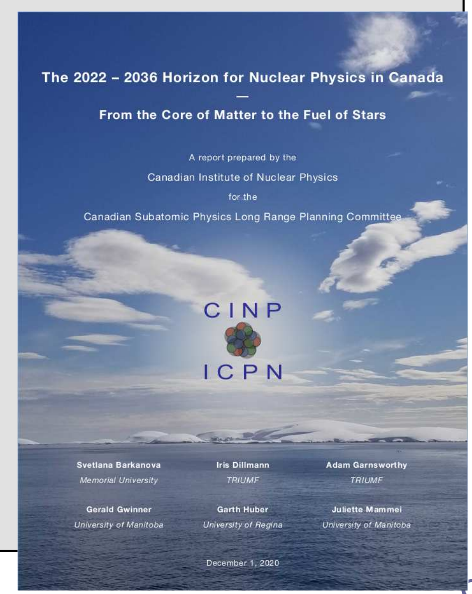
Medium term (2022–26): **Majority of domestic program is carried out at ISAC, complemented with off-shore activities at GSI, GANIL, RIKEN, FRIB**

- **The flexibility of several ISAC detectors to be combined allows a wide coverage of experiments that are not easily possible elsewhere, e.g. EMMA + TIGRESS, GRIFFIN + DESCANT, TITAN EBIT + 8π, etc. detectors.**

Longer term (2027-36): **Canadian program will profit from full implementation of ARIEL facility at TRIUMF**

– New detectors planned to take full advantage of upcoming photofission beams and intense re–accelerated heavy nuclear beams from ARIEL, e.g. EXACT–TPC

– **TRIUMF Storage Ring (TRISR)** Proposal for a low–energy storage ring with a neutron generator at ISAC is underway


The 2022 – 2036 Horizon for Nuclear Physics in Canada

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From the Core of Matter to the Fuel of Stars

A report prepared by the

Canadian Institute of Nuclear Physics

for the

Canadian Subatomic Physics Long Range Planning Committee

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Svetlana Barkanova, Memorial University

Iris Dillmann, TRIUMF

Adam Garnsworthy, TRIUMF

Gerald Gwinner, University of Manitoba

Garth Huber, University of Regina

Juliette Mammei, University of Manitoba

December 1, 2020

What physics lies beyond the Standard Model?

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- Nuclear physics, and closely associated experiments at the precision frontier, have played an important role for many years in searching for new physics beyond the SM.
- Advantages of this community are the diversity of efforts, nimble response to the changing landscape, relatively modest budgets, and diverse HQP training.
- Increasingly, a connection is forming to the emerging field of “quantum sensing”, or more broadly “quantum technology”, promising major gains in experimental sensitivity.
- **Canada continues to punch above its weight in this domain, with numerous efforts at two world–class domestic facilities, TRIUMF, and SNOLab, as well as abroad, for example at JLab and CERN, covering most aspects of searches for physics beyond the SM.**

What Physics Lies Beyond the Standard Model?

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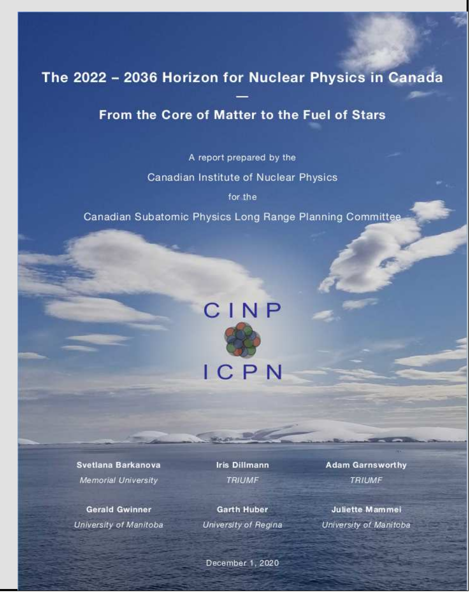
Medium term (2022–26):

- Active ISAC program: Laser–trapped Francium, GRIFFIN β–decay, TRINAT, TITAN
- TUCAN and ALPHA–g CFI–funded upgrades completed
- NaB, nPDGamma, nHe3 cold neutron experiments underway
- MOLLER @ JLab will be commissioned ~2025, run to ~2030
- Positive funding decision awaited on nEXO 5 tonne detector

Longer term (2027-36):

- Precision spectroscopy with radioactive molecules will be major new effort @ ISAC
- FrPNC to start atomic PV run @ ISAC
  - Possible extension to cold Fr, Ag molecules
- Deployment of HAICU by ALPHA Collaboration
- Fundamental Symmetries @ EIC



CINP Recommendations

1. **Enhance Nuclear Theory Support**

   Recommend increased support at a level to allow travel and support postdocs, graduate students

2. **Maintain a diverse program of excellence in experimental and theoretical nuclear physics**

   Strongly recommend that a diverse nuclear physics program addressing all of the key questions be maintained in all funding scenarios

CINP Recommendations

CINP ICPN

3. **Fund the additional HQP needed to capitalize on new or recently–upgraded facilities**

   It is essential that a corresponding increase be made in the NSERC SAP envelope to support the research teams that will drive the scientific output from these new facilities

4. **Leverage the scientific opportunities enabled by the completion of ARIEL**

   Government of Canada support for TRIUMF to allow for operational support necessary to fully exploit the science opportunities of ARIEL (9000 hr of RIB/yr) is essential

CINP Recommendations

5. **Position Canada for Leadership in Future International Nuclear Physics Research**

   A major new project on horizon is the Electron-Ion Collider, a substantial involvement will confirm Canada's leadership role in scientific research and development

6. **Grow the Nuclear Physics Community**

   We encourage our community to seek innovative sources of funds for bridge faculty positions, so that the substantial scientific opportunities we see in the next 15 years can be best taken advantage of

CINP Recommendations

7. Foster a funding environment which enables Canadian Researchers to lead in science and discovery

a) Sufficient and versatile funding opportunities for both capital equipment and operational funding is essential. The interplay between NSERC, CFI and the new Computing Agency needs to be strengthened, so that capital, operating fund and high performance computing resource decisions are coordinated and streamlined

b) NSERC and TRIUMF should continue to provide technical resources and capabilities for construction of experiments

c) Ongoing investments in detector and accelerator R&D are needed

CINP LRP White Paper

Project Updates since Dec 1, 2020

Physics Programs at Laurentian U

- **The CINP and IPP strongly condemn the closure of the physics undergraduate and graduate programs announced last week at Laurentian University in Sudbury**
- We have jointly written a letter to Ontario, Federal and Sudbury officials, asking they take action and rectify the situation
- I have also heard from CINP members, expressing dismay at the situation, the effect this has upon the scientific program at SNOLab, and the impact on Canadian deliverables to international experiments, e.g. nEXO
- **I urge CINP members to make their voices heard. Please contact me for a list of people to write to**

DarkLight @ ARIEL Update

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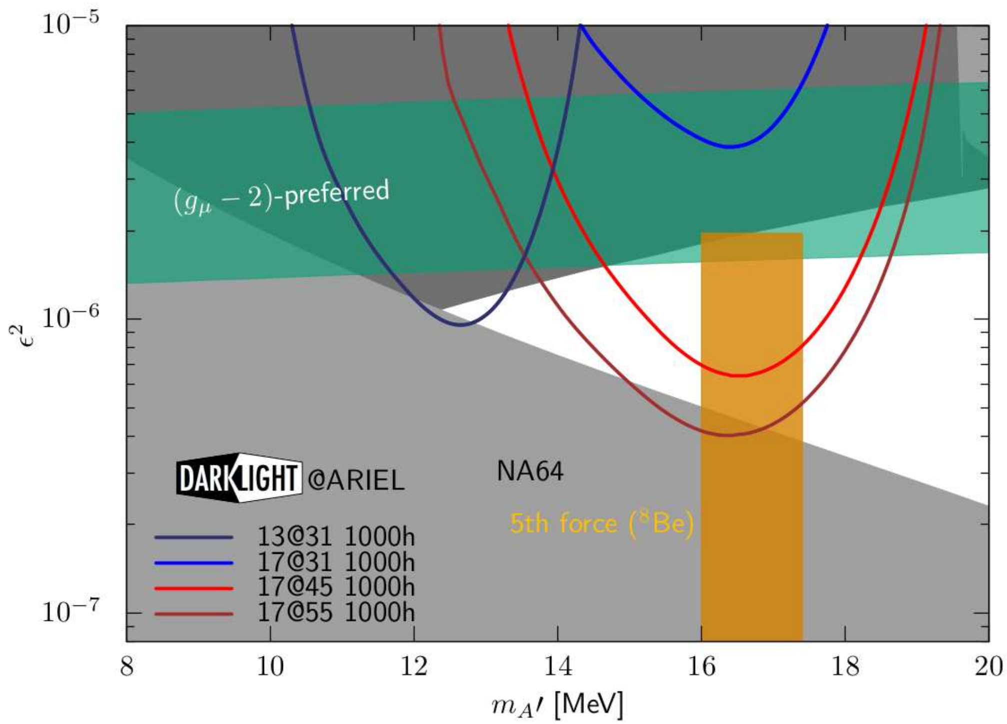
- TRIUMF has been approached by the DarkLight Collaboration to bring their experiment from JLab to TRIUMF, and to make use of the excellent electron beam from the e-linac at ARIEL
- TRIUMF reviewed their pre-proposal submission and gave them green light for a full EEC proposal. Some Canadians have joined the Collaboration
- If scientifically approved, DarkLight could take data as soon as 2022



Projected e^+e^- invariant mass reaches for three separate data taking runs at ARIEL (blue, light red, dark red).
Light gray areas are excluded by other experiments sensitive to lepton coupling.

ALPHA updates
- A Canadian-led Breakthrough

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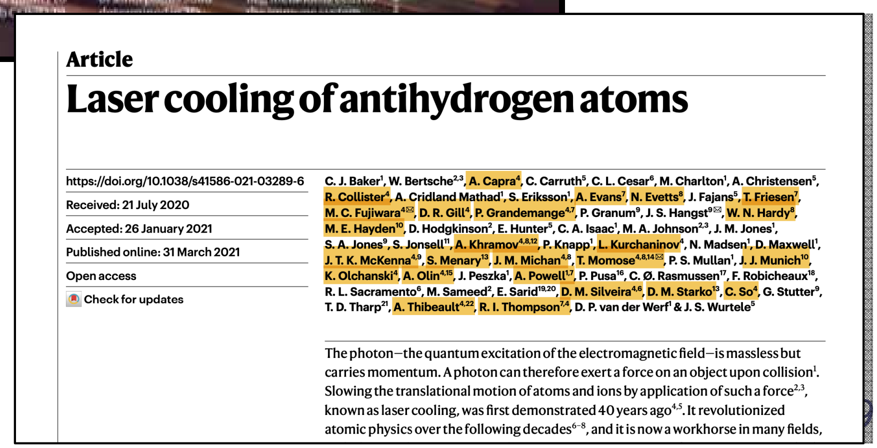
Laser cooling of antihydrogen atoms

[Nature, March 31, 2021]

- First laser-based manipulation of antimatter motion
- Intense int'l competition with ATRAP
- Canadian proposed, implemented, executed, analyzed idea
- 25 out 58 authors with ALPHA-Canada (incl. 8 students)



Article

Laser cooling of antihydrogen atoms

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Open access

Check for updates

C. J. Baker[1], W. Bertsche[2,3], A. Capra[4], C. Carruth[5], C. L. Cesar[6], M. Charlton[1], A. Christensen[5], R. Collister[4], A. Cridland Mathad[1], S. Eriksson[1], A. Evans[7], N. Evetts[8], J. Fajans[5], T. Friesen[7], M. C. Fujiwara[4]✉, D. R. Gill[4], P. Grandemange[4,7], P. Granum[9], J. S. Hangst[9]✉, W. N. Hardy[8], M. E. Hayden[10], D. Hodgkinson[2], E. Hunter[5], C. A. Isaac[1], M. A. Johnson[2,3], J. M. Jones[1], S. A. Jones[9], S. Jonsell[11], A. Khramov[4,8,12], P. Knapp[1], L. Kurchaninov[4], N. Madsen[1], D. Maxwell[1], J. T. K. McKenna[4,9], S. Menary[13], J. M. Michan[4,8], T. Momose[4,8,14]✉, P. S. Mullan[1], J. J. Munich[10], K. Olchanski[4], A. Olin[4,15], J. Peszka[1], A. Powell[1,7], P. Pusa[16], C. Ø. Rasmussen[17], F. Robicheaux[18], R. L. Sacramento[6], M. Sameed[2], E. Sarid[19,20], D. M. Silveira[4,6], D. M. Starko[13], C. So[4], G. Stutter[9], T. D. Tharp[21], A. Thibeault[4,22], R. I. Thompson[7,4], D. P. van der Werf[1] & J. S. Wurtele[5]

The photon—the quantum excitation of the electromagnetic field—is massless but carries momentum. A photon can therefore exert a force on an object upon collision[1]. Slowing the translational motion of atoms and ions by application of such a force[2,3], known as laser cooling, was first demonstrated 40 years ago[4,5]. It revolutionized atomic physics over the following decades[6–8], and it is now a workhorse in many fields,

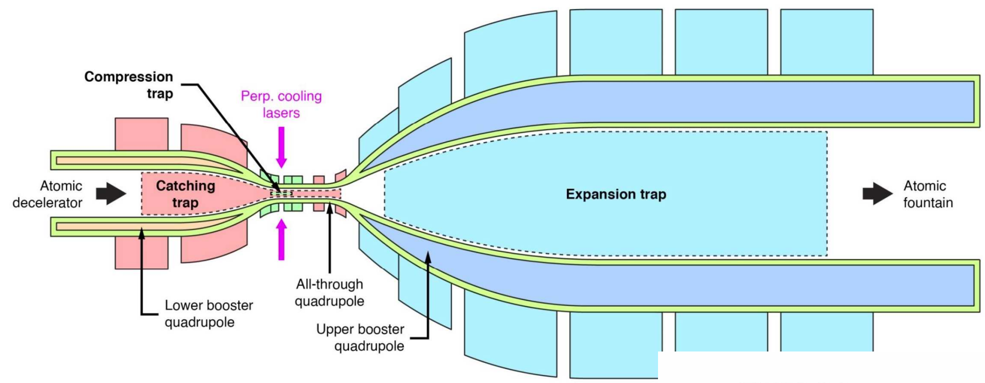
ALPHA updates

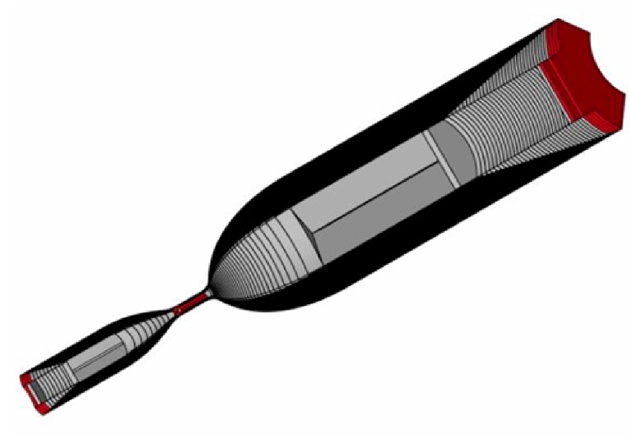
- CFI funding: Quantum Sensing with Antimatter

HAICU: Hydrogen-Antihydrogen Infrastructure at Canadian Universities

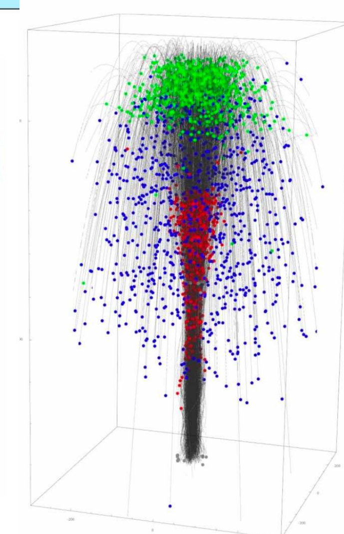
Funded by CFI-IF 2020 (awaiting Provincial matching)

- Development platform for quantum sensing technologies with antimatter
  - Use H atoms as a proxy
  - Enabled by recent laser cooling success
  - Further cooling to μK regime with entirely new concept
- Primarily goals
  - Anti-atomic fountain
  - Antimatter-wave interferometer
  - Ramsey hyperfine spectroscopy
  - Anti-molecules
  - Antimatter clocks
- Will allow dramatic improvements in precision of anti-H symmetry tests
- Aim to build an anti-H experiment at CERN in ~2025.





HAICU fountain concept (not a spaceship!)



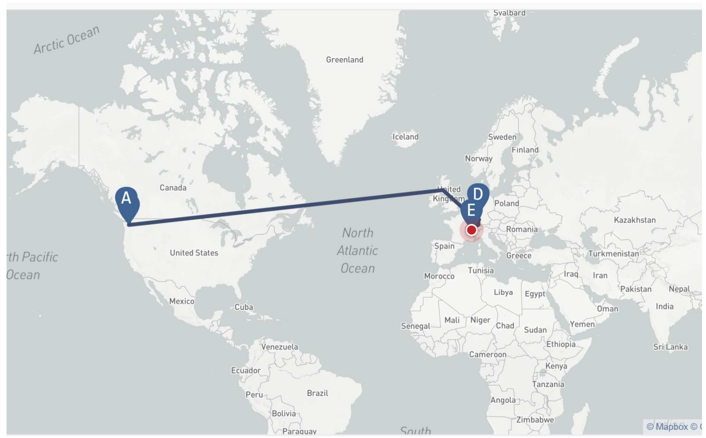
Fountain simulation

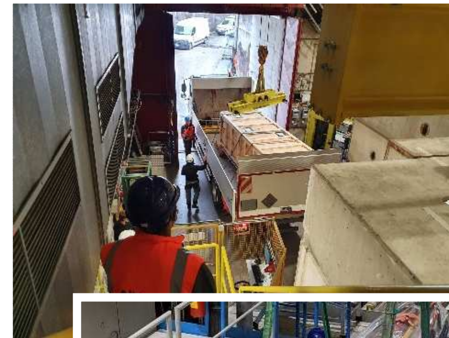
ALPHA updates

- ALPHA-g: gravity on anti-H (80% Canadian funded)

Modified radial TPC shipped back from TRIUMF to CERN, Jan 2021

CINP Summer Student, K. Liang)





- CFI-funded project (PI: R. Thompson, Calgary)
- Getting ready for commissioning with new ELENA beam in August 2021
- Will greatly benefit from laser cooling

MOLLER updates

- Significant Canadian Contributions

High precision measurement of the Weak mixing angle at low momentum transfer, using electron-electron scattering at 11 GeV

❑US$ 65M Project

- 6M NSF (approved)
- 4M CFI (approved)
- 55M USDOE (CD1 stage, first funding in 2020, CD2 in 2021)

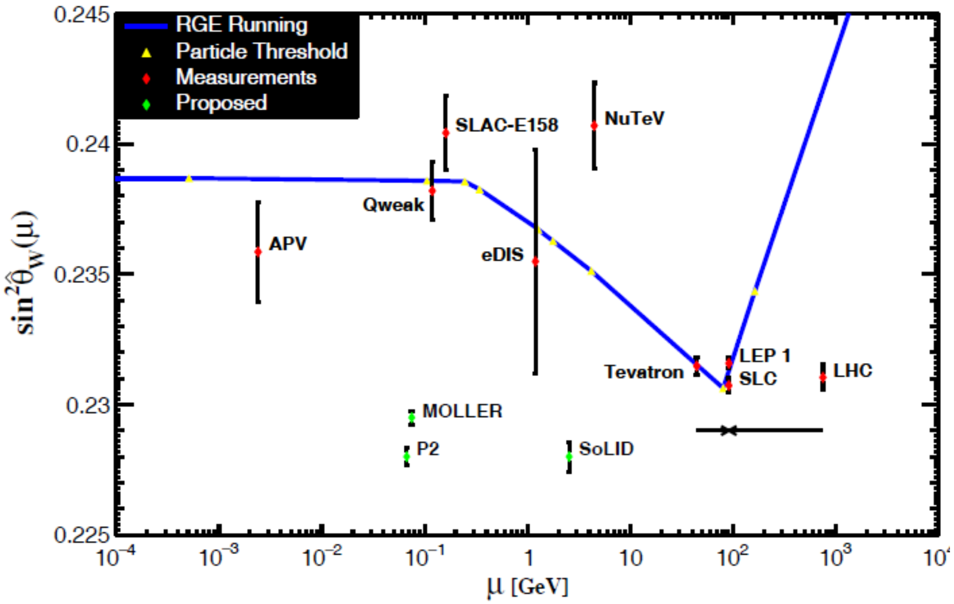
❑Current People and Schedule:

- Presently 9 faculty from U. Manitoba, U. Winnipeg, U. Memorial, UNBC
- Presently 2 postdocs and 7 students
- New U. Manitoba faculty advertisement soon
- Construction: 2022 – 2024
- Installation: 2024 – 2025
- Running: 2025 – 2027

❑Ongoing R&D Work (potential to contribute):

- General detector design and construction
- Pixel detectors (electronics / cooling / firmware / DAQ)

❑We welcome new collaborators



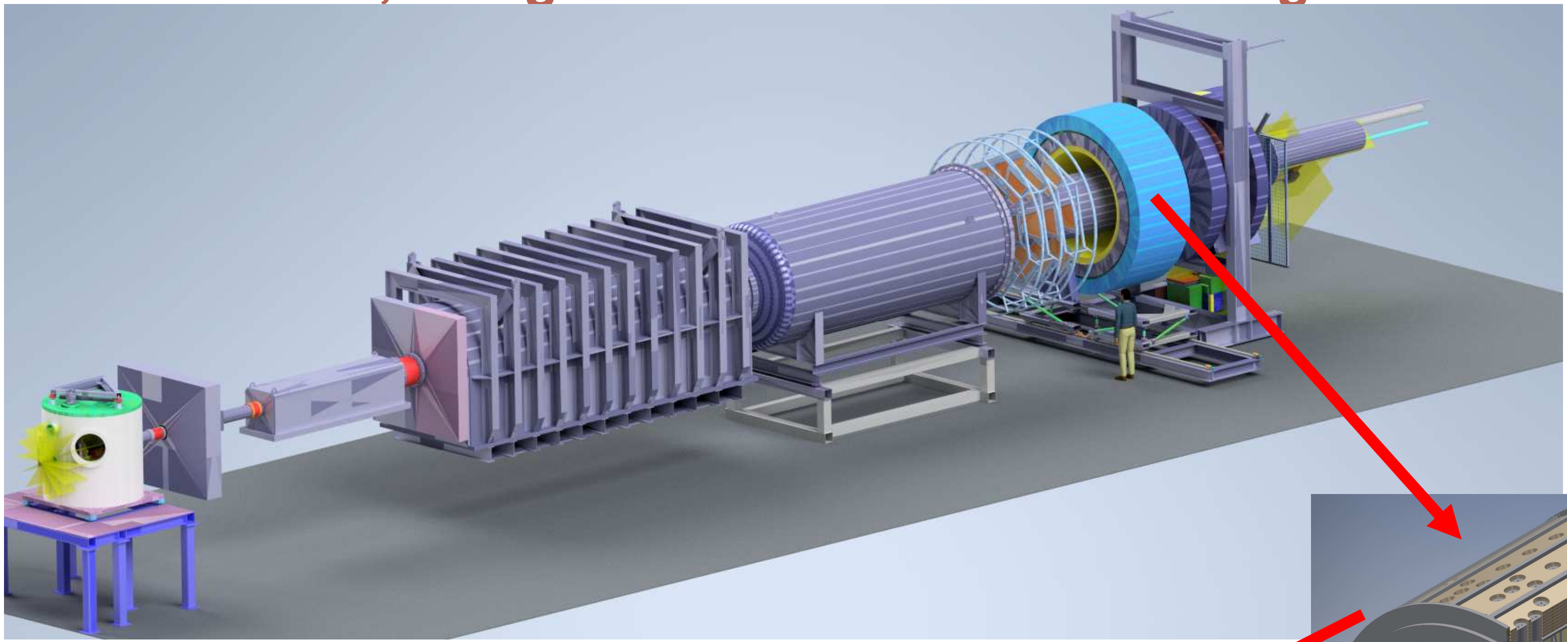
Some BSM sensitivities include:

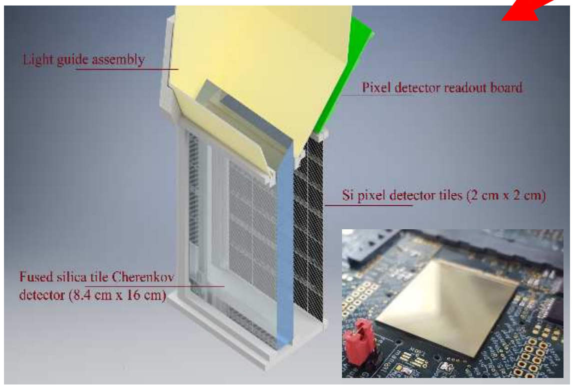
Deviations produced by

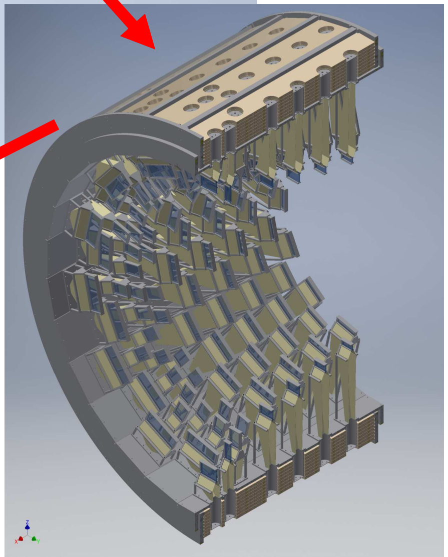
- massive Z' boson interactions
- dark photon and MeV level dark Z
- new parity-violating interactions
- lepton compositeness (47 TeV)

MOLLER updates
- CFI-IF funding approved

High precision measurement of the weak mixing angle at low momentum transfer, using electron-electron scattering at 11 GeV







- C$ 6M CFI-IF funding approved in 2020 round:
  - Main detectors: 224 quartz DIRC detectors
  - 512 Channels of electronics (preamp + ADC)
  - Profile mapper: 2688 2x2 cm HVMAP chips
  - Associated operational equipment
  - R&D and Testing Infrastructure

nEXO Searching for 0νββ at the Tonne-Scale

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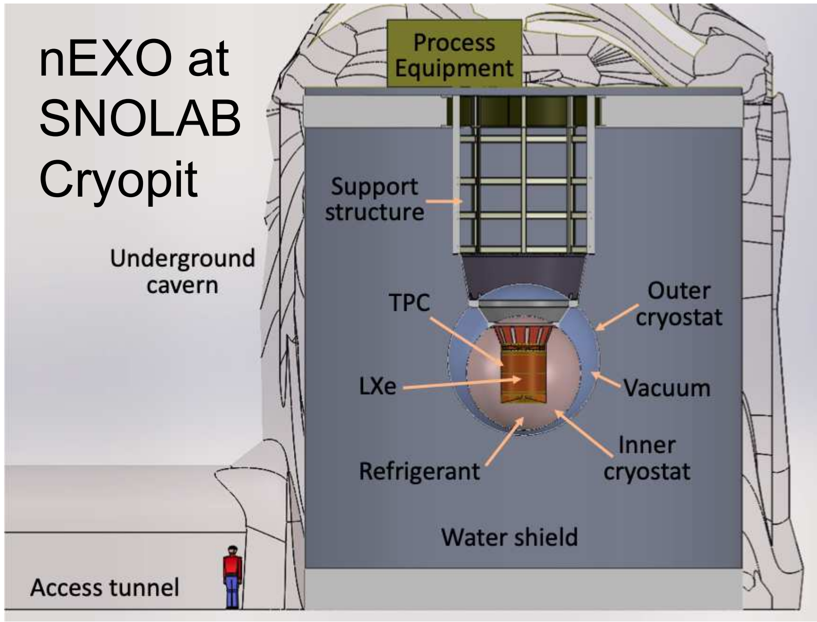
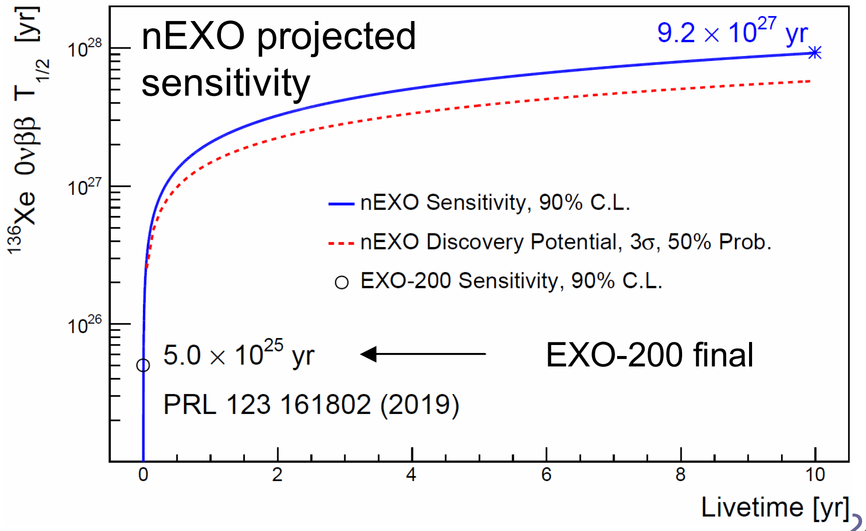
- Single-Phase Time-Projection Chamber
  - Filled with 5000kg of liquid xenon
  - Enriched to 90% in ^{136}Xe
  - Monolithic design with single drift volume with 1.3m drift length
  - Goal: energy resolution of $\sigma_E/Q_{\beta\beta} \leq 1\%$
- ~2000 m rock overburden at SNOLAB
- Active water-Cherenkov μ-veto and radiation shield
- For more details: nEXO pCDR (arXiv:1805.11142)

- nEXO projected sensitivity (Phys. Rev. C 97, 065503 (2018)):
  - Median Sensitivity: $T_{1/2} > 9.2\times10^{27}$ yr @ 90%C.L.
  - Median Discovery potential: $T_{1/2}$ = 5.7×1027 yr @ 3σ

Expect updated sensitivity study very soon!



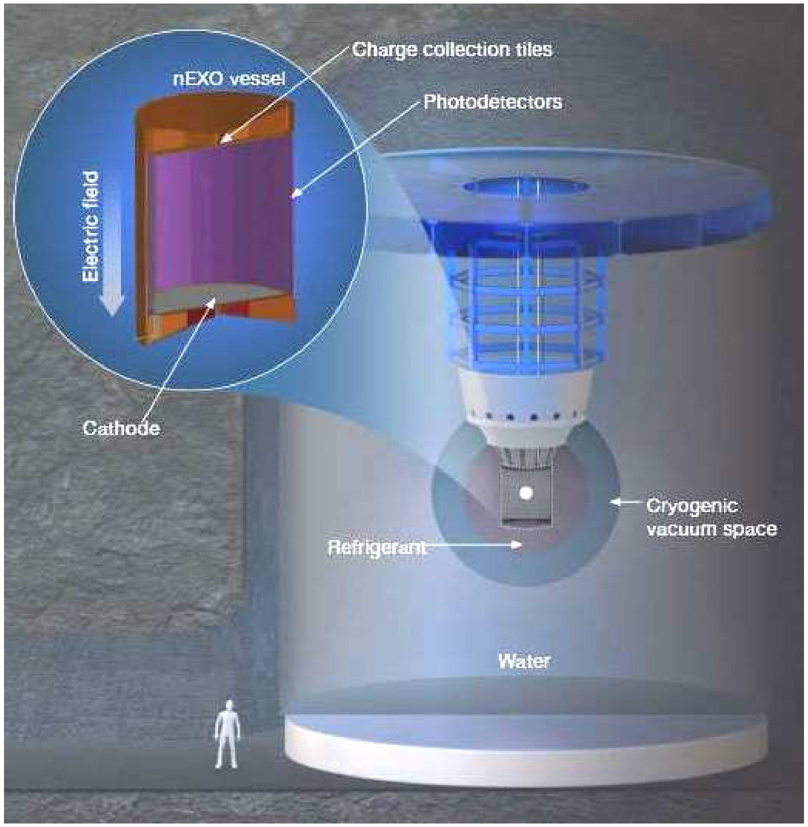


nEXO Canadian Contributions

Canadian scientists are heavily involved in the development of key-components of nEXO:

- Canadian PIs are leading the development of two detector sub-systems:
  - Outer Detector: Muon veto and radiation shield, a 1.5 ktonnes water-Cherenkov detector
  - Facility at the SNOLAB Cryopit

- Canadian PIs are contributing significantly to the development of several sub-systems:
  - External calibration system
  - Radioactive Background Controls
  - In liquid-Xe SiPM photosensors
  - Simulations



nEXO at SNOLAB

CFI Innovation Fund 2020

- **CFI-IF 2020 “Enabling the search for neutrinoless double-beta decays in Xe-136 with nEXO” (project $16.6M) has been approved under the condition that nEXO is funded by USDOE**
- The CFI will enable Canadian groups to develop critical infrastructure towards the construction of nEXO
- Components supported by CFI-IF 2020 are:
  - Infrastructure to test SiPMs at cryogenic temperatures at various stages during assembly process (Carleton, McGill, TRIUMF)
  - Muon-veto PMT test facility (Laurentian); PMTs are in-kind contribution from Daya Bay
  - Instrumentation to measure Rn outgassing rates of construction materials (Laurentian)
  - Development of novel Photon-to-Digital converters as photosensor alternative for nEXO (Sherbrooke)

Timescale and Funding Situation

- Tim Hallman, Associate Director at the USDOE Office of Science for Nuclear Physics, gave a presentation at the recent NSAC meeting with an update for the 0νββ program:
  - Double-Beta Decay Portfolio Review to be held July 13-16, 2021 to inform US investment strategy
  - North American – European Summit scheduled for September 27-29, 2021 to see if common ground exists for an international approach
  - Expectation is that more than one experiment is required to address the challenges in 0νββ searches

→ Construction and commissioning of nEXO anticipated to happen during Long Range Plan period 2022-2026; data taking expected for 10 years until ~2037

- The Canadian group is preparing a CFI-IF 2022 proposal in support of the construction of nEXO at SNOLAB:
  - Water tank and platform of the Outer Detector
  - Clean rooms in the Cryopit for the TPC assembly
  - Contributions to the instrumentation of the TPC with SiPMs

nEXO We welcome new members!

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Newest collaborating institutions:

- University of Western Cape, South Africa*
- SUBATEC Nantes, France
- Skyline College, California, US

* New collaborator Prof. Smarajit Triambak is a former TRIUMF post doc!

Electron-Ion Collider Update

Yellow Report: 800+ pages, arXiv:2103.05419

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- Executive Summary
- Volume 1: Physics
- Volume 2: Detectors

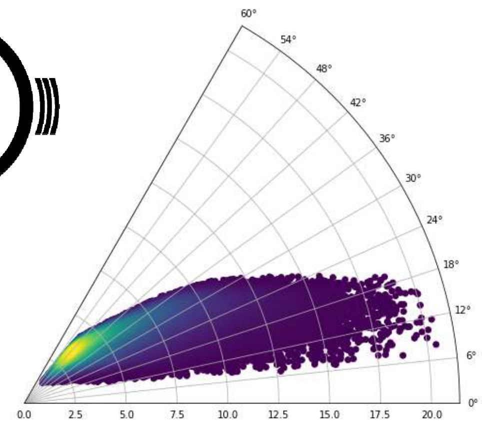
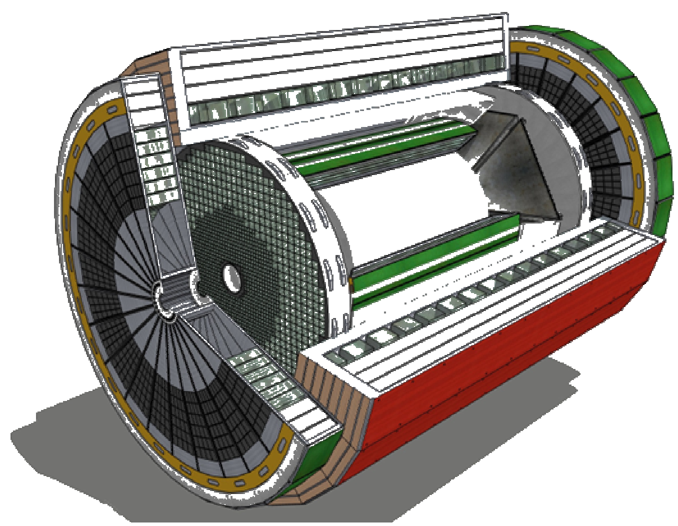


Fig 8.115: π^+ in $p(e,e'\pi^+n)$ at 5 x 41 GeV (event generator developed in Canada)

Canadian contributions:
1. Multi-Dimensional Imaging
2. Hadronization
3. Connections with Other Fields
4. Detailed Detector Aspects

Canadian leadership:
- EIC Steering Committee
- EIC Canada Collaboration

First major collider to be built in North America in the 21st century:
- **Polarized electrons** (10-20 GeV)
- **Polarized light ions** (p, d, 3He) and unpolarized nuclei → U (50-250 GeV)
- **International facility** with estimated cost US$ 1.6-2.6B



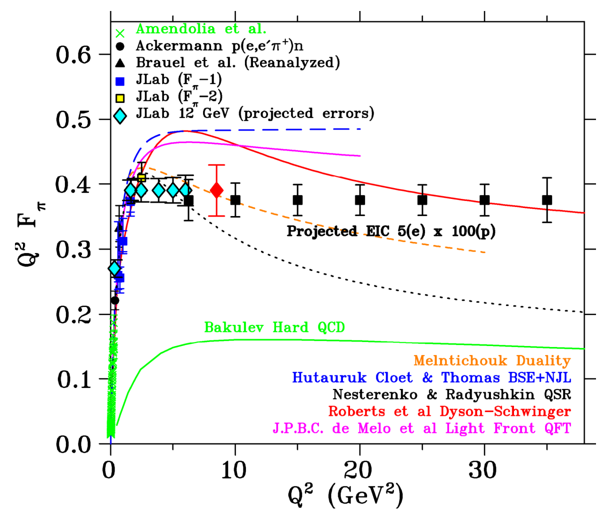


Fig 7.40: Pion form factors (U. Regina)

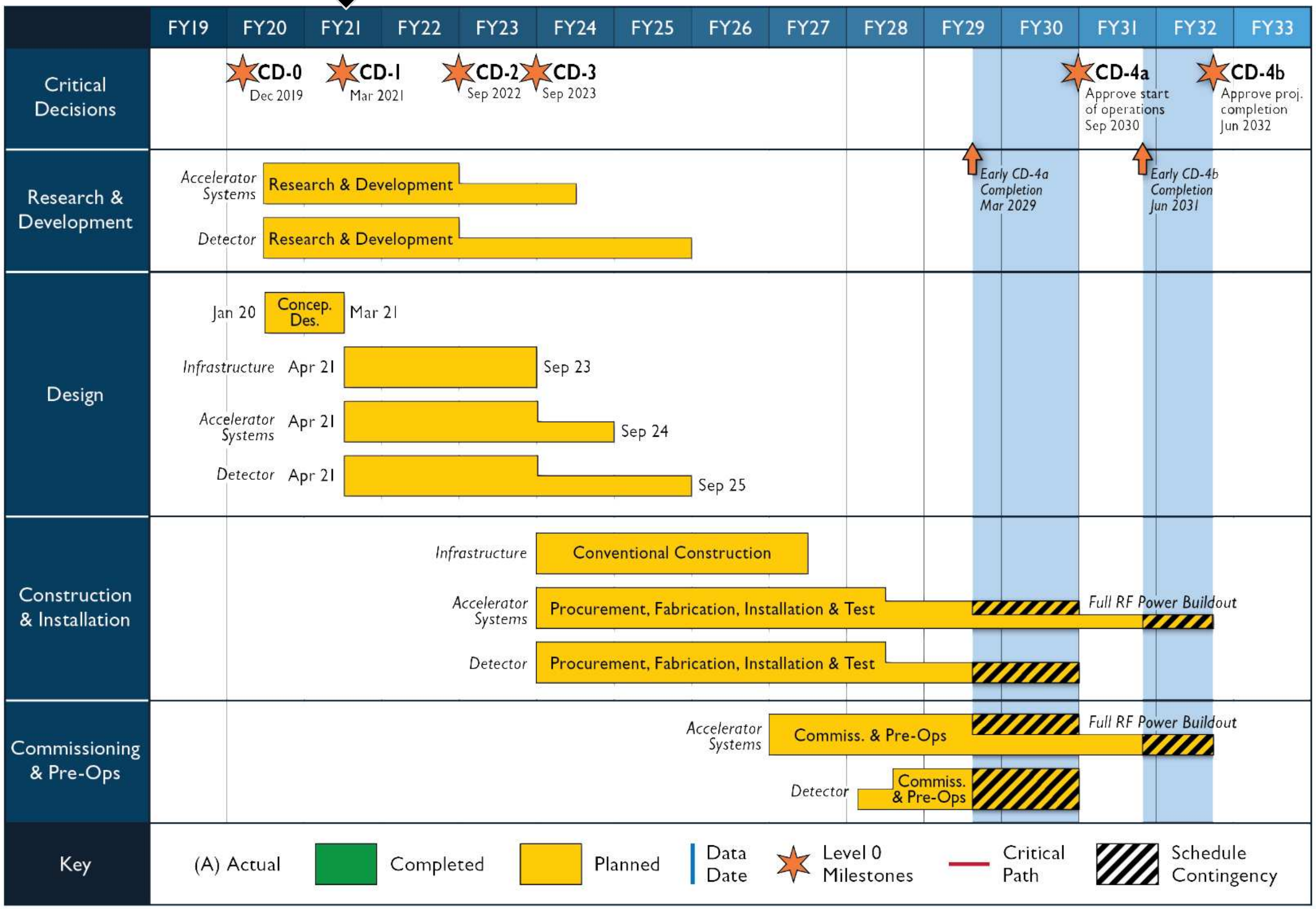
Electron-Ion Collider Update

Project Progress: Recommended to Proceed to CD-1

EIC Project Schedule:

✓January 2020: CD-0
✓2020: Yellow Report
✓March 2021: CD-1
- 2021: Collaborations
- …
- 2024: Construction and Installation
- 2030: First beam: Start of Operations

We are here right now: the start of an exciting decade



Electron-Ion Collider Update

Expressions of Interest → Collaboration Formation

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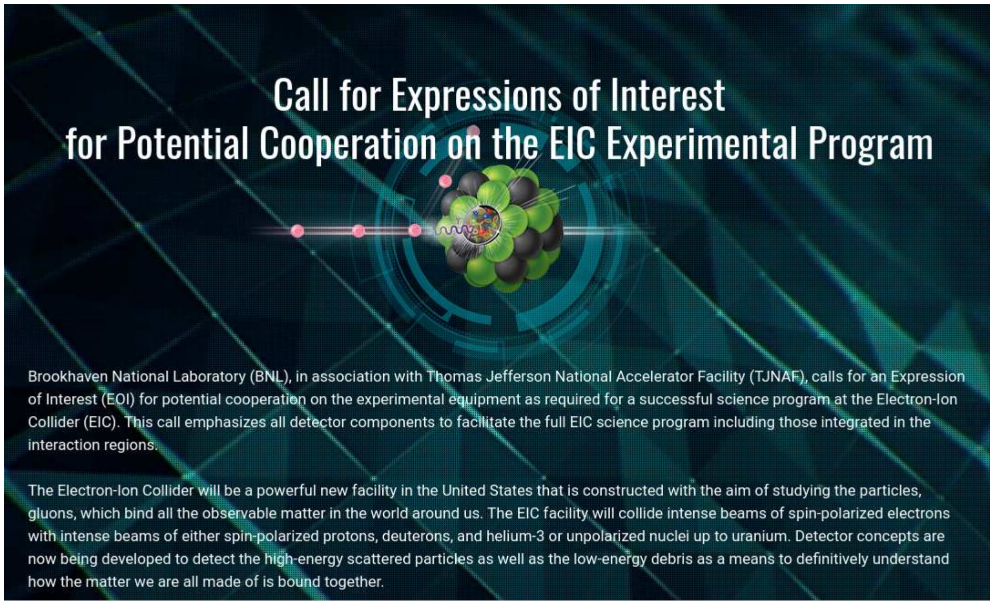
Nov 2020: Expressions of Interest



Submissions by 47 national labs, consortia, collaborations, countries, including **EIC Canada Collaboration**.

Dec 2021: Detector Collaborations

- **Detector 1 Collaboration Proposals**
  - Part of EIC Project, at interaction region 6
- **Detector 2 Collaboration Proposals**
  - Outside EIC Project, at interaction region 8

Electron-Ion Collider Update

Canadian Subatomic Physics Research Support

CINP
ICPN

NSERC Funding

- Initial operations funding secured for 4 HQP

CFI/NSERC Participation

in USDOE bilateral international meetings on EIC Science

- (incl. showcasing of Canadian highlights)

TRIUMF

- Interest in and connections on accelerator development (crab cavities, beam dynamics)

New Canadian Collaborators are very welcome!

CINP Summary

C I N P
I C P N

- Strong international consensus on the most important open questions in Nuclear Physics, as determined by comparison to NSAC and NuPECC reports from 2002–2017
- By making best use of its established expertise and strengths, and seeking to contribute to the fields of greatest scientific opportunity, the Canadian Nuclear Physics research community has self–selected where to best concentrate its efforts, in alignment with these key questions
- Strong case for increased support to maximize Canadian scientific output in nuclear physics research

Recommendation 1

- **Enhance Nuclear Theory Support**
- Advancement of nuclear physics is strongly dependent on interplay between theory and experiment
- Some examples:
  - Indirect searches for new physics at TeV scale
  - Nuclear corrections are largest systematic uncertainty in neutrino oscillation data
  - Ab–initio and phenomenological modeling identifies promising new directions for experimental work
- The key to successful collaboration is close coordination and rapid theory response to needs of experimental programs
- **Recommend increased support at a level to allow travel and support postdocs, graduate students**

Recommendation 2

- **Maintain a diverse program of excellence in experimental and theoretical nuclear physics**
- There are many inter-connections between the key nuclear physics questions, and advances in one area often follow from progress in a complementary area.
- Canadian participation and leadership in scientific experiments and developments at offshore RIB facilities should continue to be supported.
- **Strongly recommend that a diverse nuclear physics program addressing all of the key questions be maintained in all funding scenarios.**

Recommendation 3

- **Fund the additional HQP needed to capitalize on new or recently–upgraded facilities**
- Substantive progress towards the resolution of the key questions in nuclear physics requires HQP
- Despite this clear need, 2017–2021 LRP indicated broad *“capacity to train about 80% more students, if additional funding were available”*
- Recent strategic investments have enabled the development of several major new experimental facilities with very high scientific merit, and Canadians are well–placed to take advantage of these opportunities
- **It is essential that a corresponding increase be made in the NSERC SAP envelope to support the research teams that will drive the scientific output from these new facilities**

Recommendation 4

CINP ICPN

- **Leverage the scientific opportunities enabled by the completion of ARIEL**
- ARIEL is TRIUMF's flagship project, conceived to ensure Canada's leadership role in rare isotope science
- During the period covered by the LRP, ARIEL will begin to deliver science in a phased approach, allowing a large number of high priority measurements to more quickly move ahead
- **To fully leverage these opportunities, Government of Canada support for TRIUMF to allow for operational support necessary to fully exploit the science opportunities of ARIEL (9000 hr of RIB/yr) is essential**
- **Strategic operating grant investments by NSERC to ensure the dissemination of results in a timely fashion is also critical to maximize the scientific output**

Recommendation 5

- **Position Canada for Leadership in Future International Nuclear Physics Research**
- To advance our understanding of the Key Questions of Nuclear Physics, it is understood that Canadians must be leading participants in the development of major international projects
- The Electron–Ion Collider (EIC) is a major international facility on the future horizon, which will uniquely address profound question about nucleons (neutrons and protons) and how they are assembled to form the nuclei of atoms
- Canadians are involved in the planning of the EIC program, and are represented on the EIC User's Group Steering Committee
- **A substantial involvement in the EIC project will confirm Canada's leadership role in scientific research and development**

Recommendation 6

- **Grow the Nuclear Physics Community**
- Over the 15 years of the LRP, there will be a large renewal of the scientific researcher ranks of our field
- Substantial scientific opportunities, such as ARIEL and EIC, but also new international RIB facilities such as FRIB and FAIR, make the case for an expansion of investment in Nuclear Physics research in universities across Canada
- Historically, Bridge Faculty Positions have proven to be an effective way to strategically grow research capacity in highly promising fields within Canadian universities
- **We encourage our community to seek innovative sources of funds for such positions, so that the substantial scientific opportunities we see in the next 15 years can be best taken advantage of**

Recommendation 7

CINP ICPN

- **Foster a funding environment which enables Canadian Researchers to lead in science and discovery**

a) Sufficient and versatile funding opportunities for both capital equipment and operational funding is essential. The interplay between NSERC, CFI and the new Computing Agency needs to be strengthened, so that capital, operating fund and high performance computing resource decisions are coordinated and streamlined

b) NSERC and TRIUMF should continue to provide technical resources and capabilities for construction of experiments

c) Ongoing investments in detector and accelerator R&D are needed