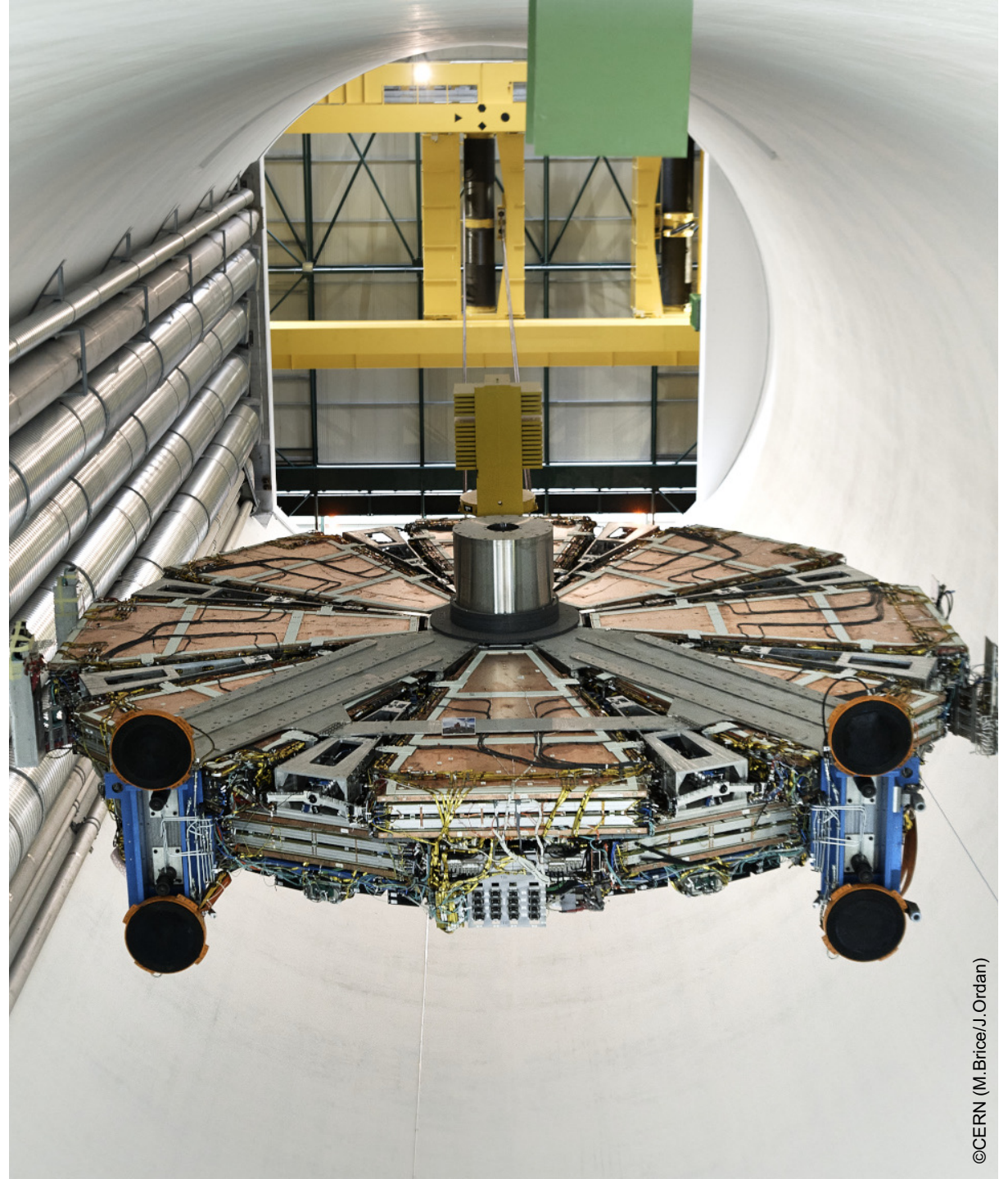


# PARTICLE PHYSICS at TRIUMF

Isabel Trigger

Physical Sciences Division



# INTRODUCTION – Particle Physics Projects

- Particle Physics projects are usually global endeavours that need highly specialized facilities – often unique in the world
- TRIUMF has facilities and expertise so Canada can **lead in Scientific Discovery** by making significant contributions to the leading experiments around the world
- Leadership requires increasing selectivity:
  - *Focus projects* with leadership maintained in all areas:
    - detector design ⇒ construction ⇒ ensure critical mass in operations & data analysis
- Particle Physics at TRIUMF focuses on:
  - High Energy Frontier
  - Neutrinos and Dark Matter
  - Precision Tests of Fundamental Interactions



From Canadian Subatomic Long Range Plan 2022-26:  
<https://www.subatomicphysics.ca>

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# INTRODUCTION – Particle Physics Projects

TRIUMF focuses on:

- Experiments at Accelerators (CERN, JPARC, Fermilab, PSI)
  - ATLAS, T2K/HyperK, ALPHA, NA62/PIONEER
- Precision measurements at TRIUMF’s own accelerators:
  - In-house program: UCN/TUCAN, PIENU, DarkLight
- Deep underground experiments at low-background labs (primarily SNOLAB)
  - nEXO, SuperCDMS, DarkSide, SNO+, HALO

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**GOAL 1**  
Make ground-breaking discoveries across our multidisciplinary research portfolio

**GOAL 6**  
Drive national and international collaboration in research, technology, and innovation

**TRIUMF STRATEGIC PLAN 2020-2025 AT A GLANCE**

**OUR VISION**  
Our vision is for Canada to lead in science, discovery, and innovation, improving lives and building a better world.

**OUR MISSION**  
Our mission is to serve as Canada's particle accelerator centre. We advance isotope science and technology, both fundamental and applied. We collaborate across communities and disciplines, from nuclear and particle physics to the life and material sciences. We discover and innovate, inspire and educate, creating knowledge and opportunity for all.

**OUR MEMBERS**

**SCIENCE AND TECHNOLOGY**  
Seizing Opportunities, Expanding Frontiers

**GOAL 1**  
Make ground-breaking discoveries across our multidisciplinary research portfolio

**GOAL 2**  
Strengthen our position as a world-leading particle accelerator centre

**PEOPLE AND SKILLS**  
Developing Talent, Increasing Access and Equity

**GOAL 3**  
Become a hub for interdisciplinary education and training

**GOAL 4**  
Inspire Canadians to discover and innovate

**INNOVATION AND COLLABORATION**  
Connecting Science to Society and Canada to the World

**GOAL 5**  
Translate science and technology into innovation and commercialization

**GOAL 6**  
Drive national and international collaboration in research, technology, and innovation

**PLATFORMS**

**ADVANCED RARE ISOTOPE LABORATORY (ARIEL)**  
Revolutionizing the study of isotopes for science, medicine, and business

**INSTITUTE FOR ADVANCED MEDICAL ISOTOPES (IAM)**  
A world-class centre for advanced isotope research and development

**TRIUMF INNOVATIONS**  
Translating scientific discovery into commercial opportunities

**OUTCOMES**

- Extension of the frontiers of knowledge and global recognition of Canada's contributions to discovery research
- Increased capacity for world-class, multidisciplinary research and development in Canada
- A new generation of highly-skilled Canadians ready to compete in the knowledge and innovation economy
- Greater access to STEM opportunities for all Canadians
- New game-changing technologies that support business-led innovation and improve the lives of Canadians
- A stronger, more competitive Canada in discovery and innovation

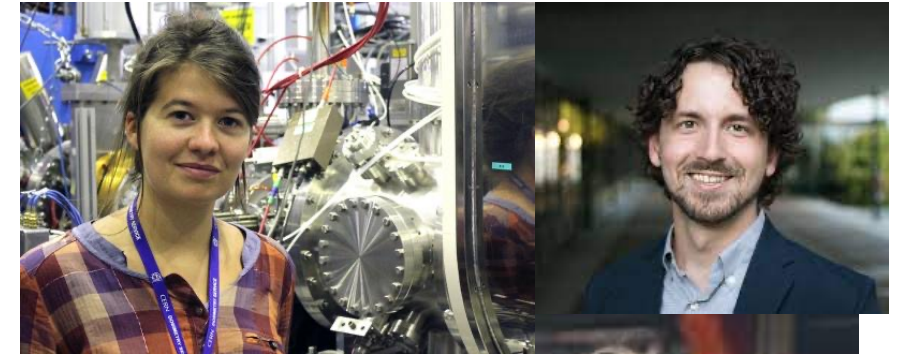
# INTRODUCTION – Particle Physics Strategic Goals <sup>4</sup>

- TRIUMF supports Canadians in globally leading discovery science, delivering breakthroughs that unlock the deepest mysteries of the universe.
- Particle Physics is a multidisciplinary effort across several Physical Sciences departments and the Accelerator Division:
  - Particle Physics, Science / Technology, Scientific Computing / Theory
- Particle Physics is *the* major subatomic focus of most TRIUMF Member Universities
  - Supporting Canadians in international Particle Physics has been one of the main strategic roles of TRIUMF since TRIUMF machine contributions enabled Canada to join the LHC in the early 90s
- TRIUMF participation meant Canadians were at the heart of two Nobel prize-winning discoveries:
  - Higgs boson discovery with ATLAS & proof that neutrinos have mass with both T2K and SNO

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# INTRODUCTION – Particle Physics People

- Substantial renewal over past five years (2018-2022):
  - New BAE hires:
    - Wolfgang Rau (2018, McDonald Institute joint position)
    - Max Swiatlowski (2019)
    - Kate Pachal (2021)
    - Chloé Malbrunot (2022)
    - Xiaoyue Li (2022)
    - ALPHA hire (in progress)
  - Newly Emeritus BAE: Toshio Numao, Stan Yen, Georges Azuelos
  - P. De Perio (2018-22, now Kavli IPMU affiliated scientist)
- Permanent joint faculty at member universities:
  - 4 remaining: M.Vetterli, D.Gingrich, P.Savard, D. Karlen
  - Recently retired: G.Oakham (2018?), R.Tacik (2020?)
- Bridging positions at member universities:
  - Thomas Brunner (McGill) 2015-2020, now Affiliated Scientist
  - Russell Mammei (U.Winnipeg) 2015-2020, now Affiliated Scientist
  - Ken Clark (Queens) 2018-2025, McDonald Institute joint position
  - B. Stelzer (SFU) 2021-2026, bridging to permanent joint position
- New Affiliated Scientists (in addition to the above):
  - Taka Momose (UBC), Barry Pointon (BCIT), Matthias Danninger (SFU)



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# EVALUATION

## Particle Physics, Question #1:

*To what extent is TRIUMF a platform for scientific excellence?*

### Particle physics connects TRIUMF and Canada to the world, and brings the world to TRIUMF

- **Particle physics explores the world at its most fundamental** and is the flagship “discovery” physics at all the major Canadian universities
  - TRIUMF enables Canadian leadership in international particle physics experiments by providing
    - accelerator expertise and components
    - detector expertise and construction facilities
    - dedicated research scientists
- **Particle physics experiments** are performed at facilities unique in the world.
  - For the highest energy accelerators, TRIUMF has collaborated with CERN for decades
  - For neutrino beams, we have deep connections with KEK and Fermilab
  - For the cleanest deepest low-background underground environment, TRIUMF has been a part of SNOLAB and SNO since inception
  - Our own accelerators and facilities are suitable for lower-energy precision measurements

Experiments from Canadian Subatomic Long Range Plan 2022-2026:

Particle Physics, at TRIUMF

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

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# EVALUATION

## Particle Physics, Question #2:

*Is TRIUMF focusing on the right areas to stay relevant to serve the needs of the TRIUMF community and beyond?*

### TRIUMF Particle Physics focuses on Canadian Priorities

- **TRIUMF is central** to Canada's Subatomic Long Range Plan
  - TRIUMF five-year plans are informed by broad discussions within the Canadian community
  - Our efforts are focused on the projects pursued by the universities
  - Science priorities at TRIUMF are driven by our member universities



## Particle Physics, Question #3:

*To what extent does TRIUMF have the capacity, competencies and facilities to achieve its objectives moving forward?*

- TRIUMF builds up **technical expertise across projects, over extended periods**
- Large shared technical groups (Design Office, Machine Shops, Sci-Tech Detector & Electronics groups) allow efficient transfer of skills and sharing of facilities
  - Collaboration with Accelerator Division is key
  - TRIUMF particle physics attracts excellent scientists and technical personnel
  - Retention of skilled people sometimes challenging – salaries need to remain competitive in a tight market, dual-career families very common in PP – but progress being made
  - Retention and development of facilities and attraction of visitors and students are challenged by limited office and lab space

# TRIUMF Particle Physicists

## Particle Physicists in Physical Sciences Division

"BAE" = Board Appointed Employee: *grant-eligible* TRIUMF research scientists

Particle Physics Department

Scientific Computing Department

Science Technology Department

Theory Department

Member Universities

BAEs, Emeriti, Post-docs, Students, Other Staff Research Scientists

BAEs, Computing professionals & computing physicists

BAEs, Engineers, Detector Physicists

BAEs, Post-docs, Students, Visitors

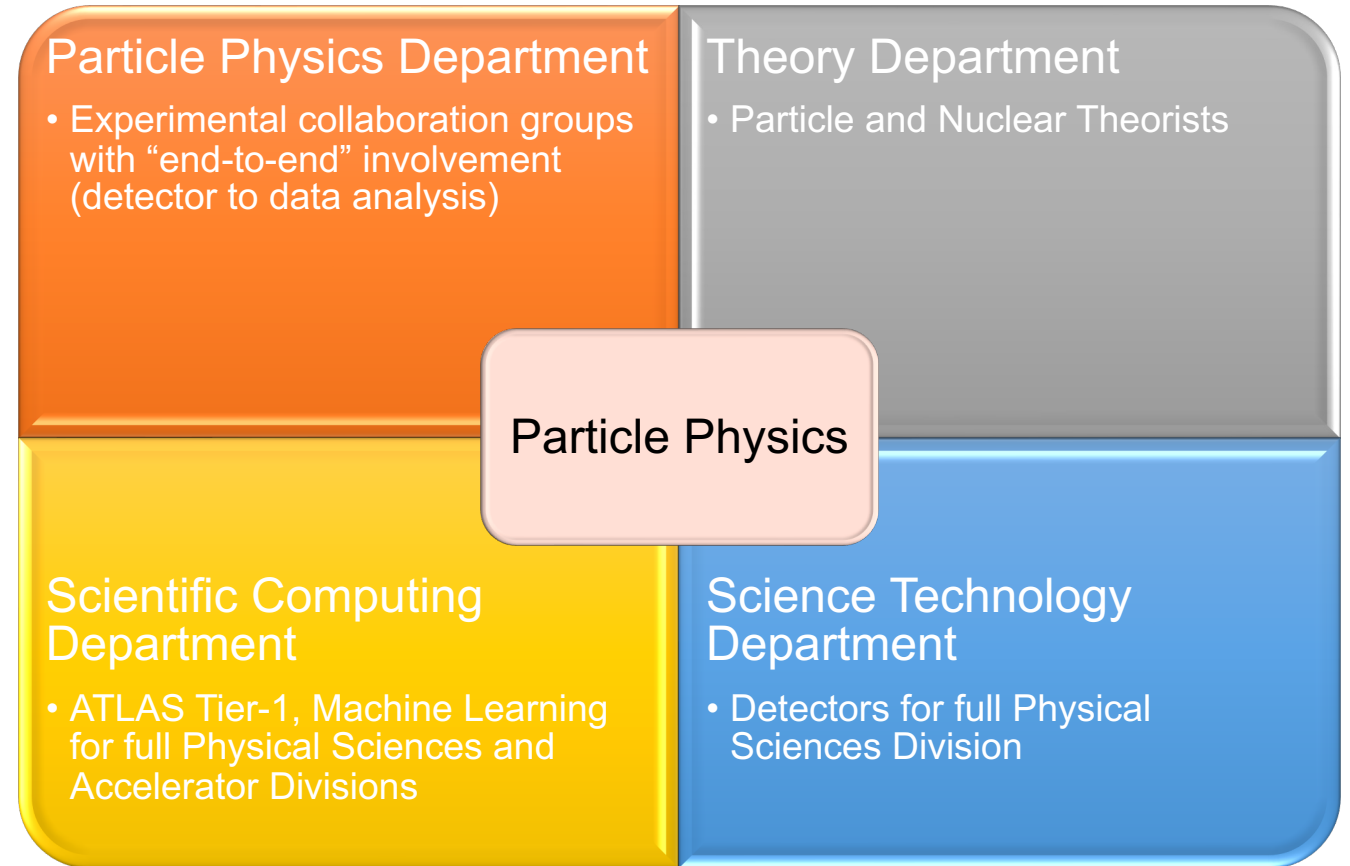
Joint Faculty, Affiliated Scientists, Students

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# TRIUMF Particle Physics Group Structure

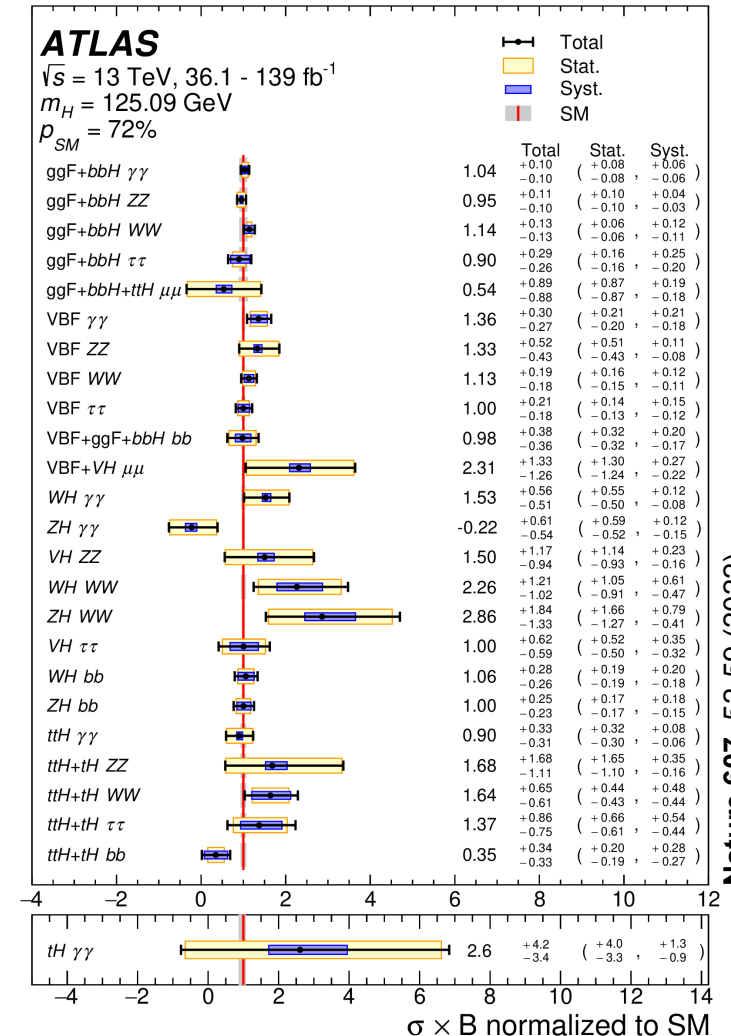
- Particle physics unites members of four departments in the Physical Sciences Division
  - Three of these departments do more than “just” particle physics
- Scientific Computing is a new department (created fall 2020) comprising Machine Learning, Quantum Computing & ATLAS Tier 1
  - Complementary to Core Computing & Networking (in IS&T under Core Services) and to DAQ Group (in Sci Tech Dep’t)



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# ATLAS Computing, Upgrades & Analysis

- ATLAS at CERN LHC: core part of TRIUMF program since 1994
- Major projects, all active through past 5 years:
  - Calorimeter, Muon Tracker & Inner Tracker upgrades (next slide)
  - Tier-1 Computing Centre: smoothly transitioned to two-site distributed centre in 2018 with new equipment at SFU
  - Accelerator Division crab cavity cryostat project for HL-LHC
  - Leadership in combined performance groups Jet /  $E_T^{\text{miss}}$
  - Detector operations: shifts, on-calls for muon detector
  - Also (obviously!) data analysis:
    - LHC Higgs Physics has transitioned from “Discovery” to precision measurements
    - There is, however, still much scope for discoveries!

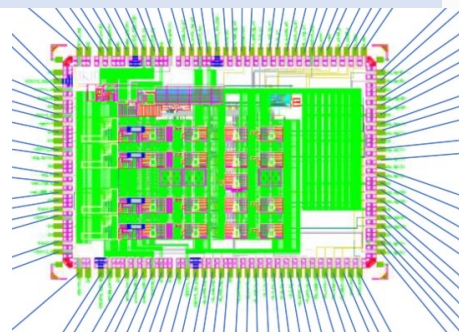


Nature 607, 52-59 (2022)



# ATLAS Calorimeters, Muon Chambers & Inner Tracker

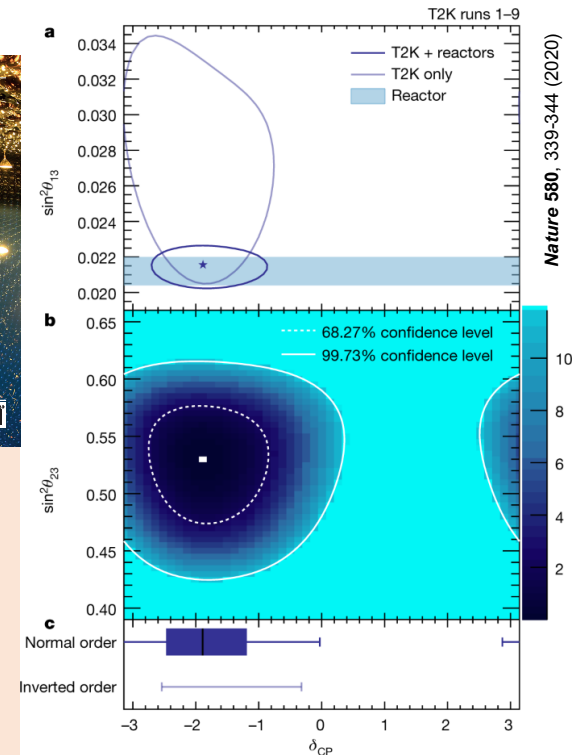
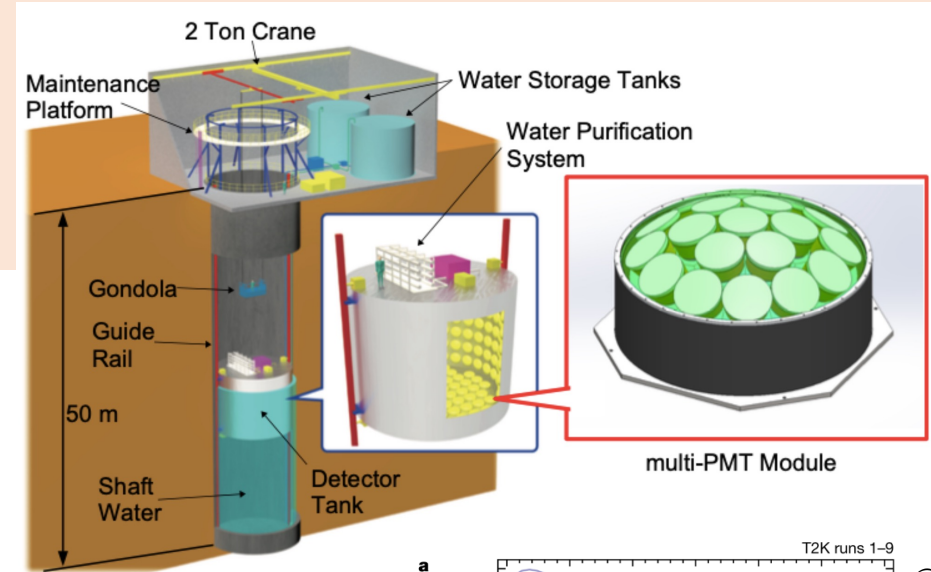
- LAr Hadronic Endcap (built at TRIUMF in late '90s to 2005)
  - Phase-1 digital trigger electronics upgrade installed & Phase-2 readout electronics upgrades (ASIC design) in progress
- Two major detector construction projects
  - Muon Spectrometer New Small Wheel thin gap chamber construction (Phase-1)
    - 2015-2020: precision construction, graphite-coating & polishing of half-gaps for  $\frac{1}{4}$  of sTGC quadruplets of NSW
    - 2018-2022: integration & commissioning at CERN
  - Inner Tracker (ITk) replacement endcap module and petal construction (Phase-2)
    - New clean room commissioned 2018
    - 2018-2022 tooling & technique preparation
    - 2023-2025 series production of 1500 endcap modules
    - 2023-2026 series production of 84 endcap petals



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# T2K, EMPHATIC, WCTE, IWCD & HyperK

- Long-baseline off-axis accelerator-based neutrino oscillation experiments with deep TRIUMF roots back to Kaon Factory proposal
- T2K is an experiment in Japan with a beam from J-PARC to the SuperK water Čerenkov detector at Kamioka
  - TRIUMF & the other Canadian groups designed and built many components, especially in the off-axis near detector
  - T2K recently published constraints on the CP-violating phase  $\delta_{CP}$  (*Nature* 580, 339-344 (2020))
- Construction of successor Hyper-K has started
  - Will have an 8X larger far detector requiring strong emphasis on reducing systematics
  - New water Čerenkov “intermediate” detector (IWCD) under TRIUMF leadership
  - Hadron production experiment EMPHATIC conceived by TRIUMF took data at Fermilab in 2018 & 2022; data analysis led by TRIUMF, accepted for publication
- TRIUMF group leading water Čerenkov test experiment (WCTE) at CERN, prototype for IWCD, took test beam data at CERN SPS in 2022



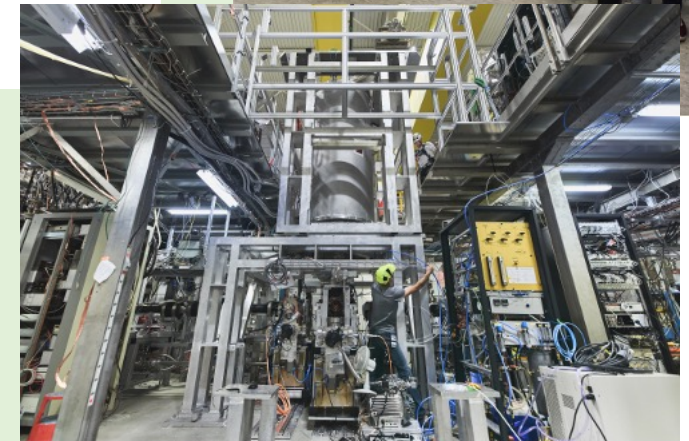
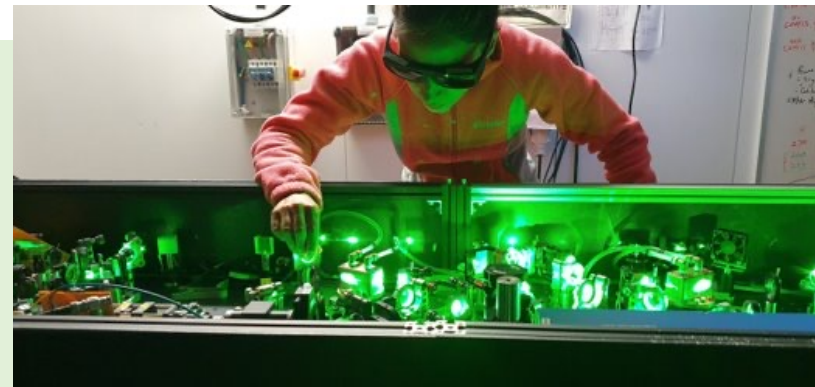
# ALPHA-2, ALPHA-g



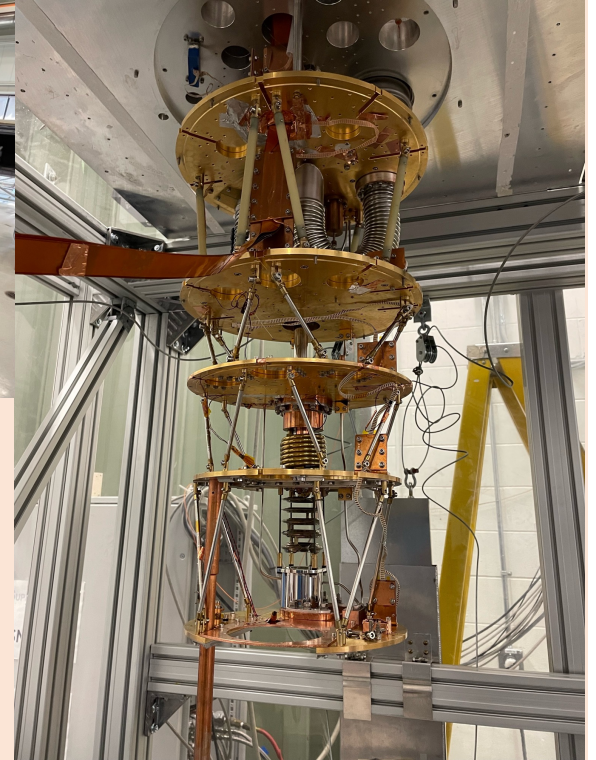
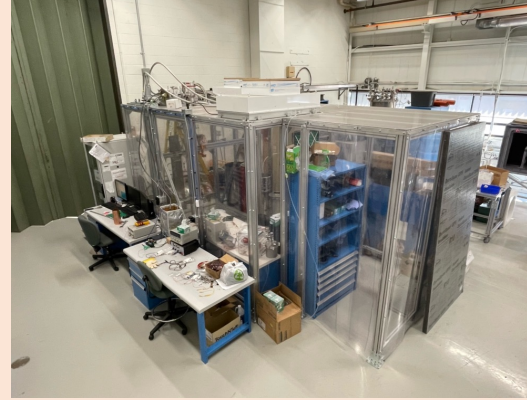
- Tests of CPT symmetry and universality of gravitational interactions between matter and antimatter using antihydrogen spectroscopy at CERN antiproton decelerator
- Test of antihydrogen charge neutrality
- Measurement of antihydrogen 1s-2s transition frequency
- Demonstration of antihydrogen laser cooling



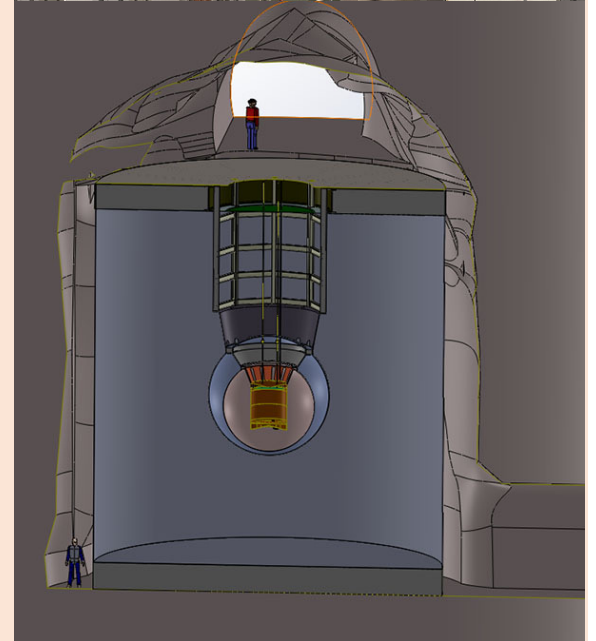
Nature 592, 35–42 (2021)



# SuperCDMS & nEXO

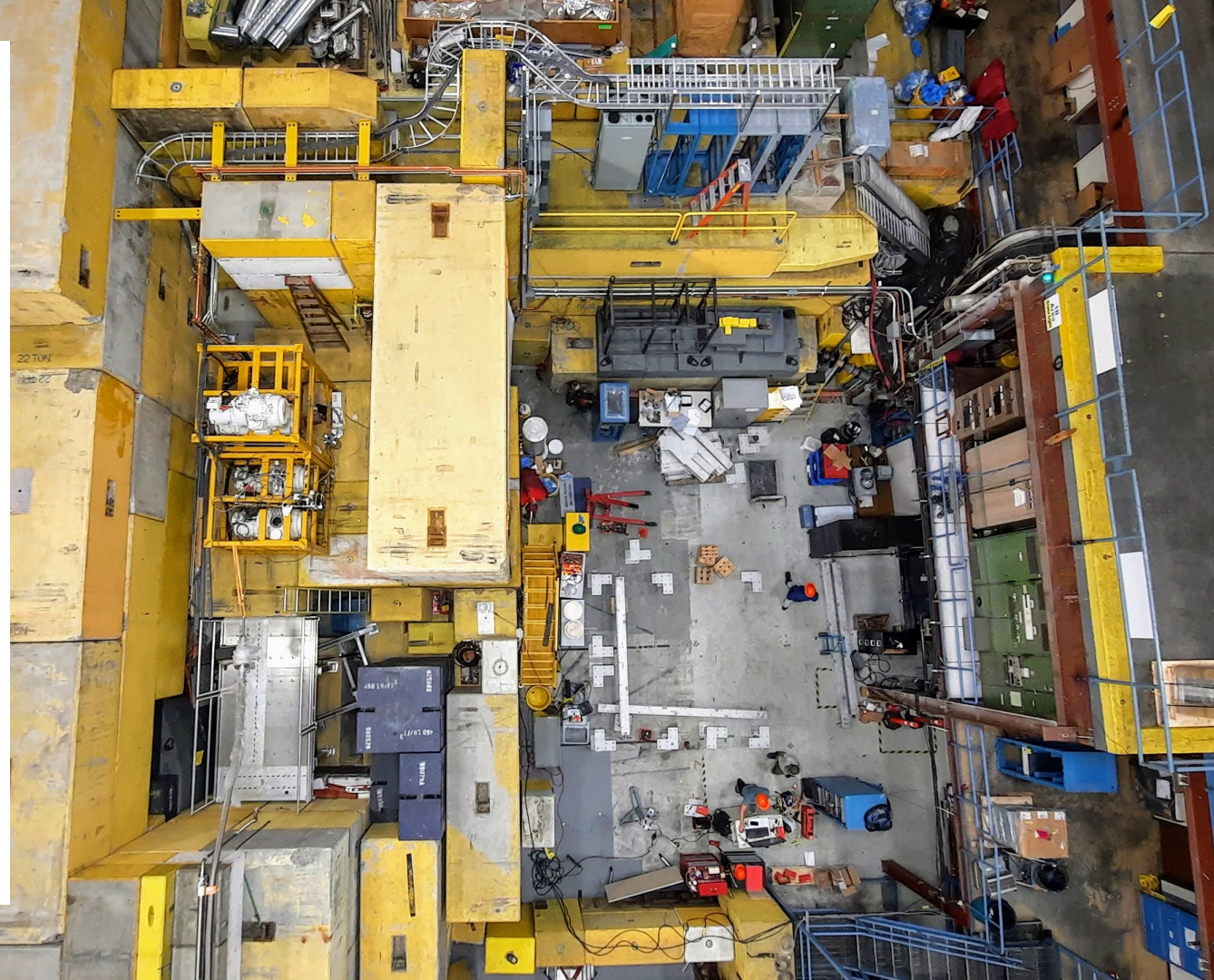


- SuperCDMS: search for low-mass WIMPs with cryogenic Ge and Si detectors
  - Currently being deployed at SNOLAB
  - Cryogenic Underground TEST facility (CUTE) for testing detectors before deployment at SuperCDMS and for early dark matter search has been built and commissioned, led by SuperCDMS groups at TRIUMF and Queen's
  - Test facility at TRIUMF for SuperCDMS detector R&D work (performance studies, calibration, etc.) installed and operational.
- nEXO: 5-tonne single-phase LXe TPC to search for  $0\nu 2\beta$  decay
  - Will be built at SNOLAB
  - TRIUMF work on SiPMs in LXe (LoLX)
  - TRIUMF nuclear physics works on barium tagging

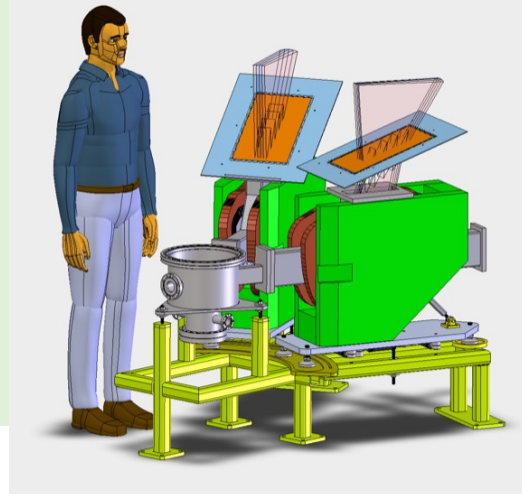


# UCN / TUCAN

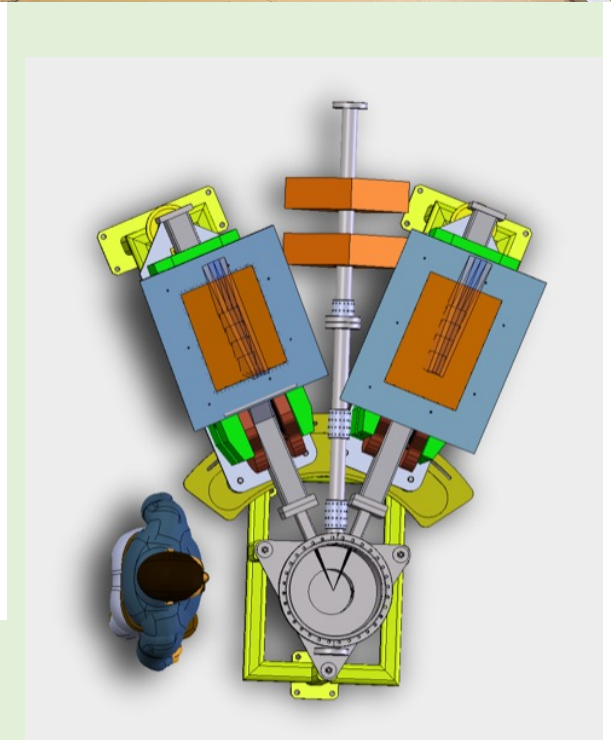
- **TUCAN is the neutron EDM experiment at the TRIUMF UCN source**
- Milestones:
  - Completion & commissioning of dedicated spallation beamline BL1U
  - Install & Operation of prototype UCN source with successful beam times 2017/2018/2019
  - Design, construction & first testing of new UCN source cryostat
    - Installation at TRIUMF in progress
    - Installation of Magnetically Shielded Room for nEDM experiment in progress
- Timeline:
  - 2024 UCN production with new TUCAN source
  - 2025 Readiness for nEDM data taking



# DarkLight



- DarkLight searches for light dark photons at ARIEL e-linac
- Experiment design converging
- Eventual e-linac upgrade to 50 MeV needed to achieve physics goal of confirming or excluding new 17 MeV boson
- First beam on test target taken in May this year
- Initial run at 30 MeV expected fall/winter 2023
- Trigger prototype in development at TRIUMF
- Accelerator team developing 50 MeV plans
- NSERC project grant awarded, CFI application via UBC to support energy upgrade





# Rare Decay Experiments: PIENU, NA62, & PIONEER

## ■ PIENU at TRIUMF

- Measured the ratio  $\pi^+ \rightarrow e^+ \nu_e / \pi^+ \rightarrow \mu^+ \nu_e$  to 0.2% resulting in the best test of Lepton Flavor Universality at 0.1% precision; produced leading searches for sterile neutrinos; additional data under analysis. Led by TRIUMF scientists.

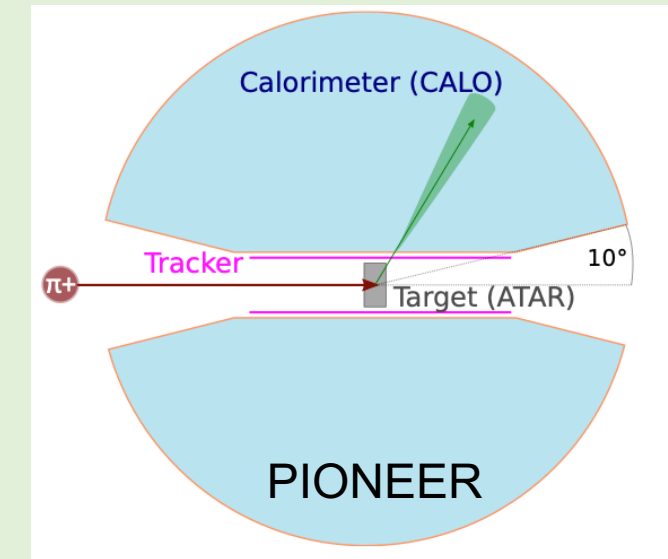
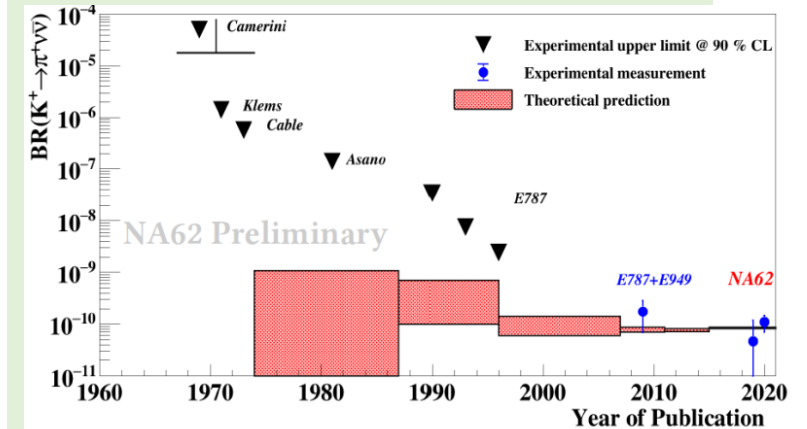
## ■ NA62 at CERN

- Measured  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  at the  $10^{-10}$  level with  $3\sigma$  significance following initial discovery at BNL; confirms precise SM predictions. Continued running will result in a 10% measurement. Also studied many exotic and SM decays, e.g.  $K^+ \rightarrow \pi^+ \chi$  which excludes feebly interacting long-lived particles in a wide range. TRIUMF has contributed to machine learning data analysis techniques, LKr purity monitoring, and other areas.

## ■ PIONEER at PSI (New)

- Aims to improve precision on rare pion decays  $\pi^+ \rightarrow e^+ \nu_e$  and  $\pi^+ \rightarrow \pi^0 e^+ \nu_e$  by an order of magnitude to 0.01% and 0.06% providing extraordinary measures of LFU and CKM unitarity via  $V_{ud}$ .
- Uses advanced technologies: Low gain avalanche detector (LGAD) tracking target and LXe scintillating calorimeter
- Initiated at TRIUMF which plays a leading role..

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  vs. Year



# Theory

- In addition to two BAE particle physicists + two emeriti, TRIUMF hosts a vibrant community of post-docs & visitors
- Dark matter, origins of matter asymmetry, searches for new particles, neutrinos & more
- Organizes workshops that bring together the international community
  - Typically at least one major workshop per year
- Close connections with particle theory groups across Canada and beyond



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# SUMMARY: Particle Physics

1. To what extent is TRIUMF a platform for scientific excellence in particle physics?
  - Design and construction of detectors / detector components for experiments at CERN (ATLAS, ALPHA, WCTE), JPARC (T2K/HyperK), SNOLAB(SuperCDMS, nEXO), PSI (PIONEER)
  - Discoveries from ATLAS, T2K & ALPHA led to 2 Nobel prizes (2013, 2015), 3 Breakthrough Prizes, 1 Polanyi Prize
2. Is TRIUMF focusing on the right areas to serve the needs of the TRIUMF community and beyond?
  - Particle physics projects at TRIUMF include nearly all major particle experiments in the Canadian Subatomic LRP – we are guided by the needs of our community
  - Expanding scientific computing to bring the growing field of machine learning to all departments and divisions
3. To what extent does TRIUMF have the capacity, competencies and facilities to achieve its objectives moving forward?
  - Several very strong BAE hires over past four years as TRIUMF renews itself
  - Dedicated Detector & Electronics group with specialization in SiPMs, light sensors, silicon sensors
  - During this period ATLAS Tier 1 computing centre outgrew its original home at TRIUMF with new equipment installed at SFU, but still maintained and operated by the TRIUMF team
  - TRIUMF built several new clean rooms and spaces for specialized tooling; however, some large (and expensive) pieces of equipment for which no immediate use was identified had to be eliminated due to lack of space
  - Connections with Accelerator Division, Nuclear Physics Department and Theory Department uniquely position TRIUMF Particle Physics at the heart of Canadian particle physics

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Thank you  
Merci

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Photo: Maximilien Brice, CERN