Building for Discovery: Overview of the Fermilab Program

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Snowmass Community Summer Study
University of Washington, Seattle
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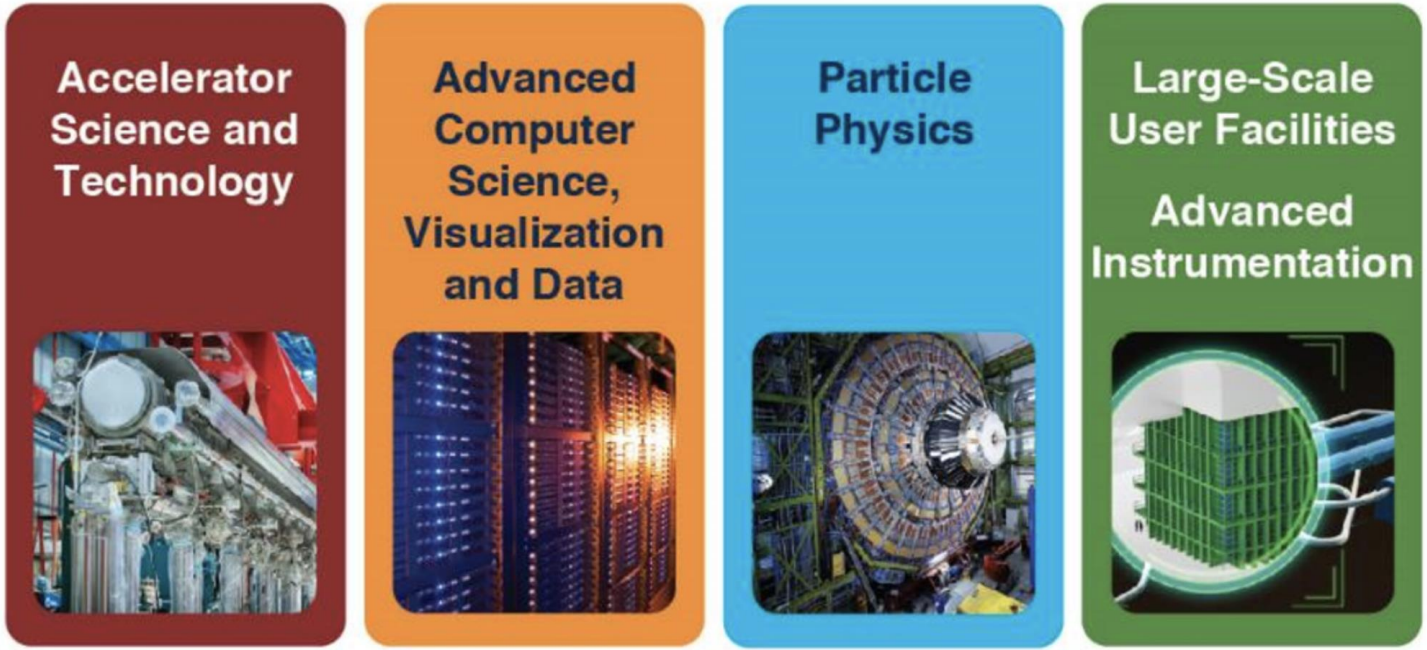
Fermilab at a Glance

- America's particle physics and accelerator laboratory
- Operates the largest US particle accelerator complex
- ~1,900 staff and ~$600M/year budget
- 6,800 acres of federal land
- Facilities used by 4,000 scientists from >50 countries

As we move into the next 50 years, our vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.

Fermilab Core Capabilities

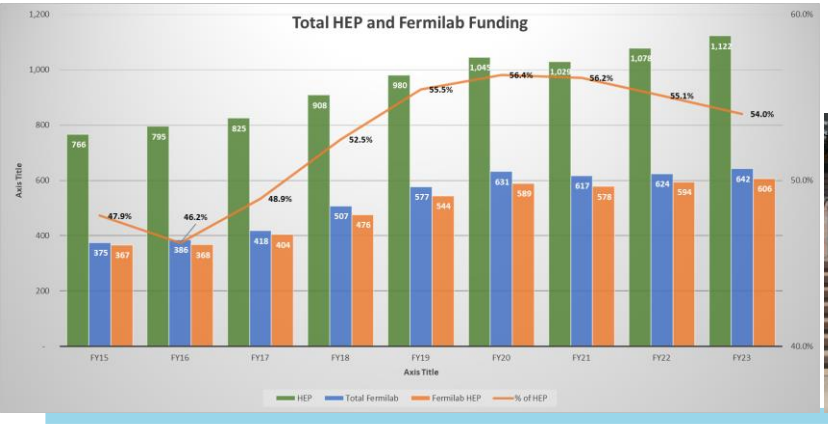


The Fermilab research community

- More than 4,000 scientists in 55 countries use Fermilab and its particle accelerators, detectors and computers for their research
- That includes more than 2,200 scientists from 175 U.S. universities and labs in 41 states
- Fermilab is attracting and training the next generation of a diverse HEP scientific workforce: 114 postdocs, 273 graduate students, 52 undergraduate interns
- Fermilab scientists also work at CERN, Sanford Underground Research Facility (SURF), SNOLAB, Cerro Tololo Inter-American Observatory, South Pole Telescope, NOvA Ash River Laboratory, Matter-wave Atomic Gradiometer Interferometric Sensor

Fermilab following the P5 strategy

- The flagship projects LBNF/DUNE/PIP-II, HL-LHC anchor the program but take many years to realize
- Fermilab simultaneously pursues a broad research effort in HEP
- The goal is a continuous stream of exciting results that attract/build/retain a diverse user community and scientific workforce
- Fermilab projects drive funding growth for HEP



Major Science & Technology Initiatives


Neutrino science and LBNF/DUNE


Collider science


Precision science


Cosmic science

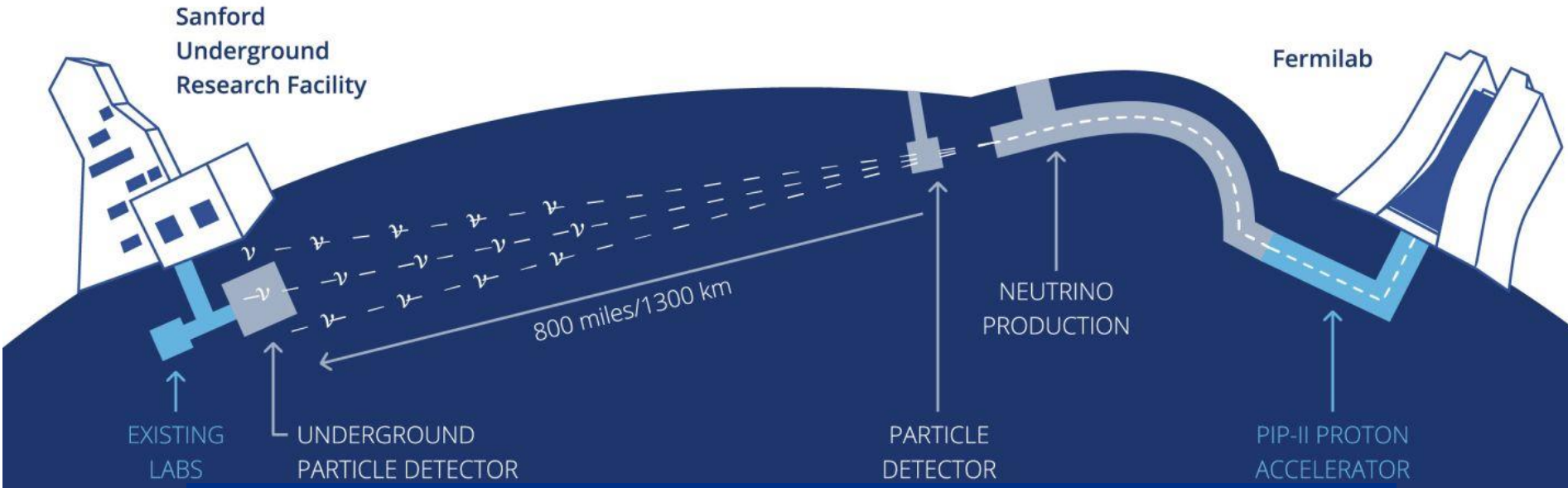

Accelerator science & technology

S&T

DUNE: The world's most capable neutrino experiment, driven by LBNF and PIP-II

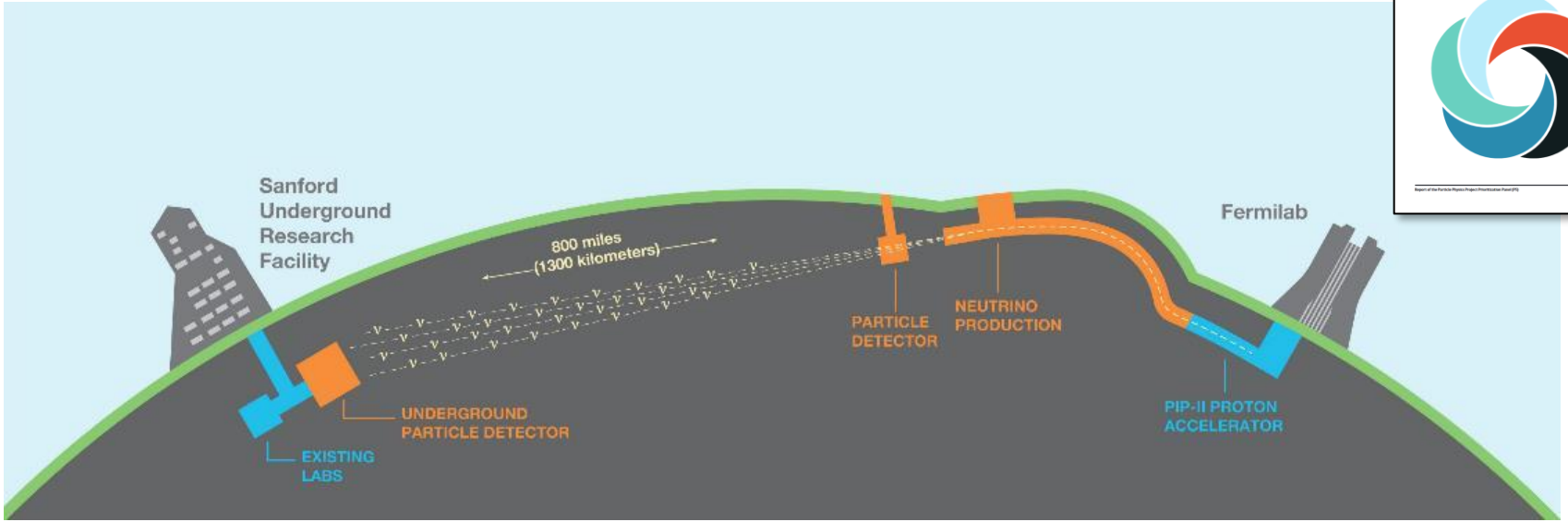
Vision for Neutrino Science

US/Fermilab is universally acknowledged as the world leader in neutrino science for decades to come



Delivering on LBNF/DUNE is Fermilab's highest priority

Science Objectives



Origin of matter. Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?

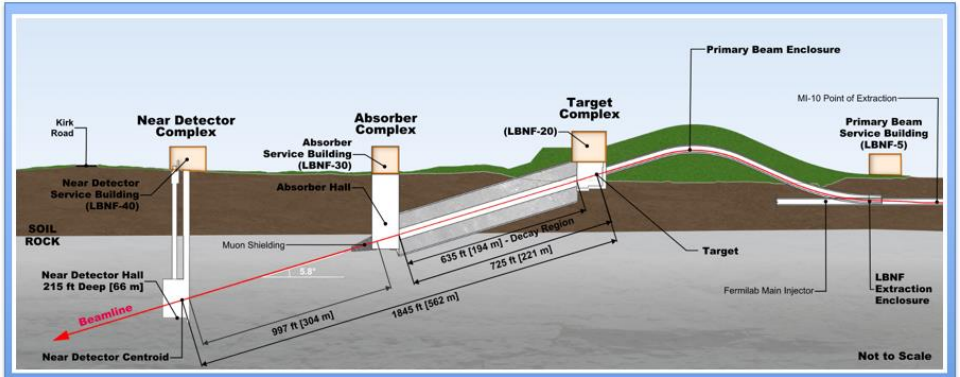
Neutron star and black hole formation. Ability to observe neutrinos from supernovae events and perhaps watch formation of black holes in real time.

Unification of forces. Investigate nucleon decay, advance unified theory of energy and matter.

The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States" – DOE

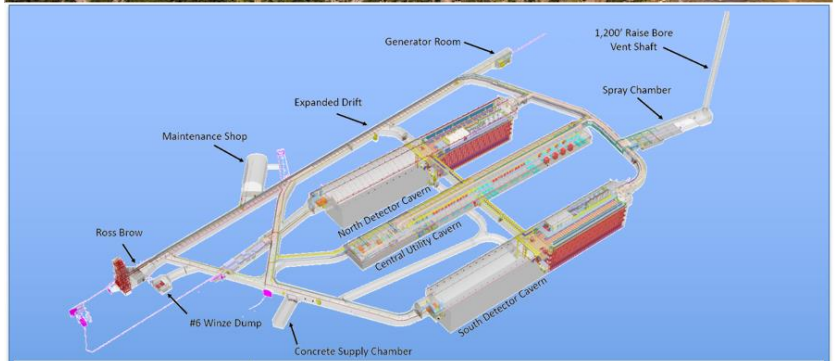
LBNF/DUNE-US Project Scope

Near Site – Batavia, IL



WBS/Subproject	Scope
131.NSCFB/NSCF + Beamline	1.2MW primary and neutrino beam, upgradable to 2.4MW; facility to support 1.2MW upgradable beamline and ND Complex
131.ND/Near Detector	DUNE-US contributions to Phase 1 Near Detector; LAr and LHe systems to support ND; installation and integration for detector and cryogenic systems.

Far Site – SURF, Lead, SD



WBS/Subproject	Scope
131.FSCFEXC/FSCF-Excavation	Project management, preliminary and final design, reliability/infrastructure upgrades, pre-excavation systems, and excavation work to support 4 detector modules.
131.FSCFBSI/FSCF-Building & Site Infrastructure	Project management, preliminary and final design, and construction of surface and underground utilities, and infrastructure outfitting of spaces for detector modules.
131.FDC/Far Detectors and Far Site Cryogenic Infrastructure	DUNE-US contributions to two DUNE detector modules; two cryostats & associated liquid argon; cryogenic systems to support two detector modules; installation and integration for two detector modules and cryogenic infrastructure

Over 50% of scope is at final design maturity

LBNF/DUNE

The DUNE experiment is managed by the international DUNE Collaboration – Fermilab is Host Lab

Collaboration statistics (as of July 2022)

1,402 collaborators, 47% U.S./53% non-US

206 institutions from 37 countries including CERN

DUNE spokespeople

Gina Rameika, Fermilab

Sergio Bertolucci, former CERN Director of Research

Demographics *(not including computing)*

- 654 facility/senior staff
- 249 post docs
- 324 grad students
- 154 engineers

- **International Engagement Office** established to consolidate coordination with DOE, U.S. community, and international partners to ensure success and impact of DUNE and entire P5 plan
- **Host Lab Task Force** being established, headed jointly by CRO and COO offices – July 2022

Fermilab is preparing to host the international DUNE collaboration

LBNF/DUNE-US: Status and recent achievements

- Project will be executed through 5 subprojects — total TPC stable at $3130M
- Far site excavation proceeding on time and on budget, approaching 33% complete and in baseline approval process – ESAAB is scheduled in July
- Detector installation begins 2024; CERN and partners ready for production
- DOE provided new funding profile that accelerates “beam on date” to Mar 2031
- CD-1RR review in July 11-15

LBNF/DUNE-US CD-1RR DOE Review Key Takeaways

- Strong support for the competitiveness and complementarity of DUNE and Hyper-K
  - "…If neutrino physics is more complex than can be parameterized in the PMNS matrix this complementarity will become even more invaluable."
- Considerable improvements across the entire project
  - New funding guidance from SC significantly improves project
  - Technical progress in all 5 subprojects
  - Project culture and atmosphere: "open,.. transparent,.. disciplined"
  - "Project team is the strongest that the committee has seen on this project … working well and focusing on the important issues"
- The design/build-to-cost strategy with a not-to-exceed-cost constraint is starting to have a positive impact…. There is a need to constantly reinforce and execute to this approach
- Vision for Fermilab as host lab for LBNF/DUNE program and collaboration validated. The focus of the entire laboratory organization is giving priority to LBNF/DUNE.
- Project costs are understood and stable since 2019. The project should work with DOE HEP on the approach to external conditions, incl. COVID, inflation, supply chain (affecting all SC projects) and proceed to CD-1RR ESAAB with a more conservative estimate of the cost and schedule range.

Strong preference to keep the total project cost close to $3130M – will explore ways to accommodate potential growth e.g. descoping, off-project scope, additional partners

Proton Improvement Plan – II (PIP-II)

PIP-II Project construction begins!

- PIP-II received DOE CD-3 approval for start of construction/execution on April 18
  - Linac complex RFP issued
- Front end of PIP-II linac constructed and successfully tested with beam
- PIP-II cryoplant building 98% complete
- HB650 prototype cryomodule in assembly – first of its kind

PIP-II is the first particle accelerator built in the U.S. with significant international contributions

LBNF/DUNE/PIP-II in-kind contributions $1.1B with growth potential

- LBNF/DUNE-US
  - $262M in-kind contributions to LBNF (does not include private @ $70M or State of SD @ $93M to support SURF)
  - $310M in contributions to DUNE detectors
  - $84M in CERN contributions to protoDUNE efforts (does not include French contributions to protoDUNE R&D)
- Additionally, LBNF powered by PIP-II, which has secured $310M in international contributions

- All in-kind contributions are expressed in DOE TPC units
- Numbers do not include other IKCs received in support of Fermilab's short-baseline neutrino program

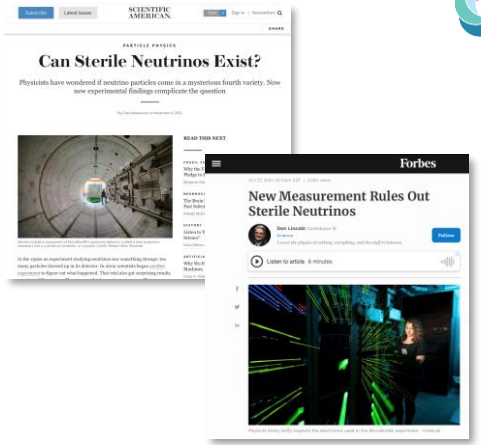
In-kind contributions supported by 10 Government-to-Government agreements and 17 I-CRADAS

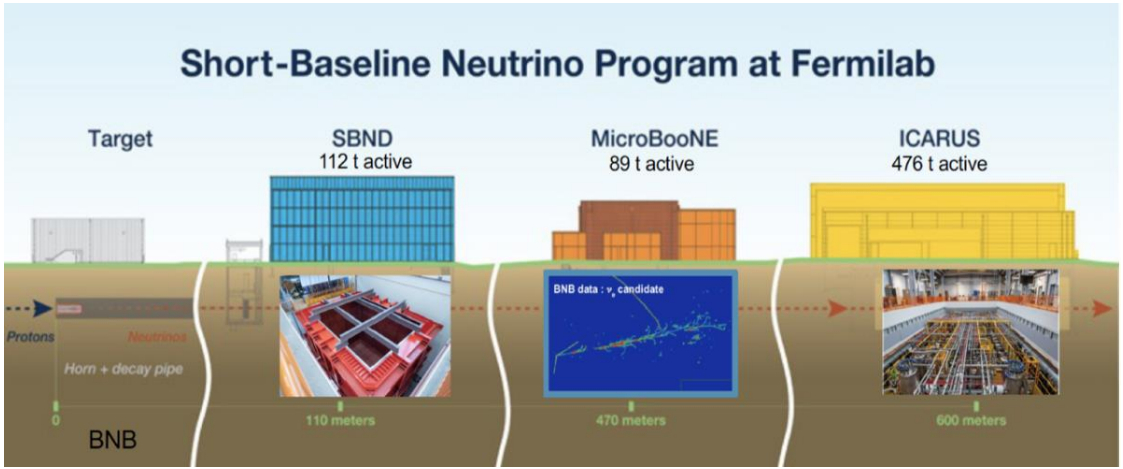
Fermilab

Short Baseline Neutrino (SBN) program

The SBN program is a P5 report recommendation:
Pursue an exciting accelerator-based short baseline neutrino program at Fermilab, SBN

- to attract national and international neutrino community to Fermilab
- perform experiments using liquid argon detector technology – basis of DUNE
- establish and train diverse community of researchers needed for DUNE





MicroBooNE made a big splash with its recent flagship results:

- Liquid argon technology works extremely well, good news for DUNE
- Seven papers released simultaneously

Science target: resolve the 4.8σ MiniBooNE low energy excess, with the possibility of discovering sterile neutrinos or other exotic neutrino physics


Collider Science and
the US CMS Collaboration

S&T Collider Science

Vision: Fermilab continues to be the leading U.S. center for CMS and second leading center in the world after our partner CERN

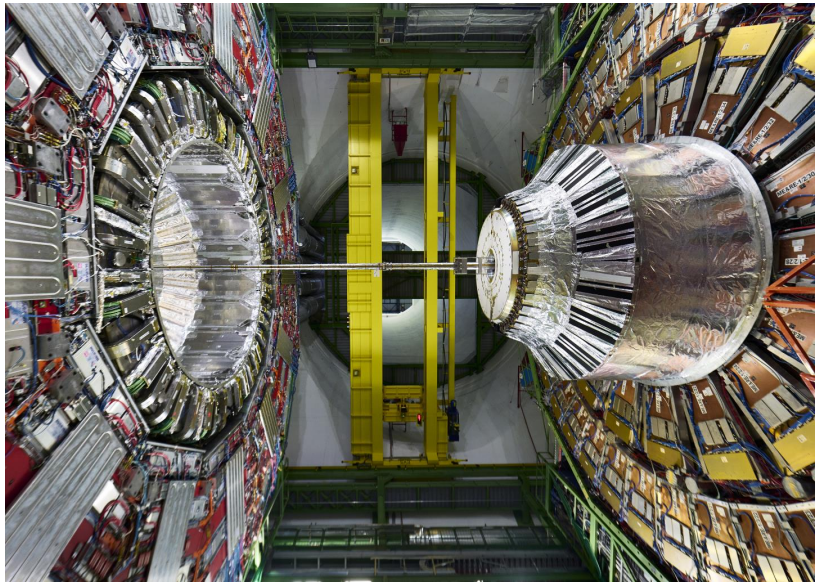
Discovery Potential

New insights into the building blocks of the universe, searching for new particles including those that could make up dark matter

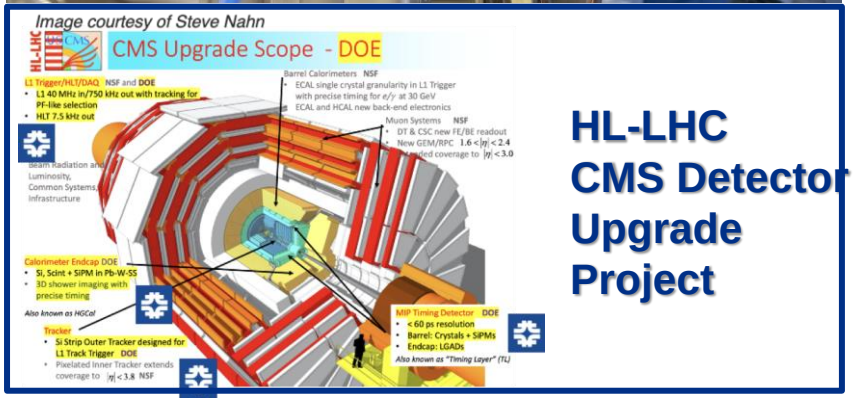
CERN is our European sister laboratory and our strong partner in many areas

- For more than two decades, Fermilab has played a significant role in the LHC
- Now CERN playing a significant role in DUNE
- Fermilab is host lab for US CMS (27% of CMS)

Fermilab's Patty McBride elected next CMS spokesperson



World-leading capabilities / recent achievements
Collider Science



HL-LHC CMS Detector Upgrade Project

Recent Achievements

CDF collaboration at Fermilab announced most precise measurement of W boson mass to be in tension with the Standard Model, April 2022

- Continued extracting science from data collected during LHC Run 2, **1100+ publications as of today**
- World class science expected with early data thanks to increased collision energy and novel detector capabilities, including software and computing
- **Advanced HL-LHC AUP and HL-LHC CMS detector upgrade projects**
  - AUP received CD-3 approval and CMS CD-3b (CD-2 scheduled FY23)
- **Fermilab's Patty McBride elected CMS spokesperson**

Fermilab Accelerator and Detector R&D supports HL-LHC Upgrades and the Future Circular Collider (FCC) at CERN

Fermilab

Fermilab as the Host Laboratory for US CMS

- **Forefront for Computing and Software in HEP Community**
  - Tier-1 facility - World's largest CMS Tier-1 facility outside CERN
  - Infrastructure to exploit HPC
  - Cutting-edge R&D
- **Host of the LHC Physics Center (LPC)** established center of excellence - Research, training, user support

- **Remote Operations Center is Back in Operations!**

- First ROC in the World to be qualified for online DQM shifts
- Unique facility that enables USCMS members to take shifts in the US
  - Efficient knowledge exchange thanks to large critical mass at the lab
  - Allowing USCMS members to perform research at the LPC while taking shifts

Fermilab

S&T Precision Science

Vision: Fermilab is a world center for accelerator-based Charged-lepton flavor violation (CLFV) and Dark Matter experiments, driven by intense particles beams and PIP-II/Booster Replacement

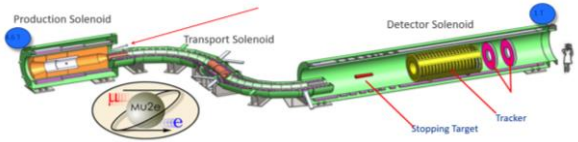
Discovery Potential

The Muon g-2 and Mu2e experiments use muons, particles that we can produce and control, as a probe of possible new forces or quantum phenomena beyond the Standard Model.

Fermilab Associate Scientist, Tammy Walton with the **Muon g-2 ring**

Fermilab Associate Scientist, Jessica Esquivel with her #IfThenSheCan statue at the Smithsonian

Mu2e



Baseline Change Review (FY23)
Project complete CD-4 (Q3FY25)

PIP-II and Muon Campus infrastructure enables future precision science experiments

Fermilab

S&T Cosmic Science

Vision: Fermilab is an essential partner in world-leading cosmic science experiments and is contributing innovative R&D efforts toward future dark energy, dark matter, and cosmic microwave background (CMB) experiments. The Cosmic Physics Center will unify the activities at the laboratory and in the Chicagoland area, in particular UChicago and ANL, while serving a national cosmic user community.

Discovery Potential

Surveys of galaxies and cosmic background radiation use precise measurements of cosmic structure to learn about fundamental physics of cosmic acceleration, new forms of matter, and properties of cosmic neutrinos. A coordinated campaign of experiments seek to directly detect and study the properties of dark matter particles in the laboratory.

World-leading capabilities
Cosmic Science

These capabilities/resources support national cosmic frontier program: DES, DESI, Super CDMS, SENSEI/Oscura, ADMX, SPT-3G, CMB-S4 and R&D

Fermilab

S&T Accelerator Science & Technology

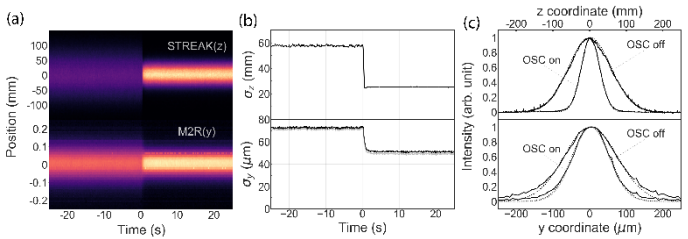
Vision: Fermilab is a world-leader in Accelerator Science and Technology R&D that enables the next generation of particle accelerators and advances the HEP and Office of Science mission. Fermilab is an essential partner of choice to future large-scale accelerators.

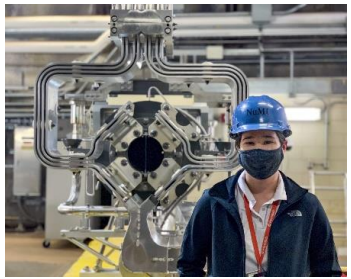
Discovery Potential

Future accelerator-based experiments will be enabled by more intense beams, higher accelerating gradients and more power accelerator magnets.

Fermilab's IOTA/FAST Facility provides a unique platform for accelerator science

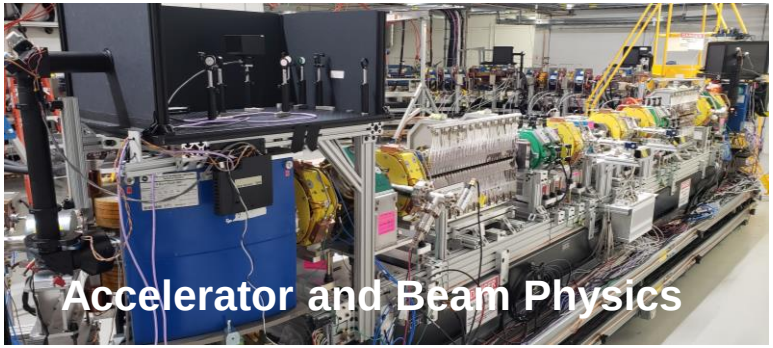
- World's first experimental demonstration of Optical Stochastic Cooling at the IOTA ring (accepted to *Nature*)





Fermilab

World-leading capabilities
Accelerator Science & Technology



Fermilab is addressing the needs of many SC program offices

Fermilab

Fermilab Accelerator Complex User Facility Modernization

Vision/Goals

- Highly effective, efficient accelerator operations with a modernized control system, work and lab spaces and integration of emerging technologies like robotics and AI/ML for accelerators

Key Initiatives

- **ACORN**: DOE O413 project to modernize the accelerator control system and replace end-of-life power supplies; partnership with INL for user interface and human factors expertise
- **Robotics Initiative**: Motivated by need to increase worker safety and efficiency for accelerator and target operations
- **CAST**: Proposed building to potentially include updated Main Control Room, co-located controls and instrumentation staff and space for USPAS, visiting scientists and engineers

Recent Achievements

- Completed Accelerator Operations Requirements Workshops – broad labwide participation; documented requirements for AI/ML for accelerator ops, cyber security, ES&H, software development, etc.
- Completed Robotics Strategic Plan and initiated partnership with National Robotics Engineering Center (NREC) at Carnegie Mellon

Fermilab visitors Tia Miceli, Adam Watts, and Mayling Wong-Squires with CHIMP (CMU Highly Intelligent Mobile Platform) at NREC

Largest accelerator complex in the U.S. and the only one in the world to produce both low- and high-energy neutrino beams and enable precision science experiments

Fermilab

Emerging Science & Technology Capabilities

Quantum Information Science & SQMS
Artificial Intelligence / Machine Learning
Microelectronics

S&T

Quantum Information Science

Vision: Fermilab, together with Chicagoland partners, is a major US quantum center; hosts national facilities for Quantum Science, developing innovative approaches that enable HEP discovery.

Fermilab quantum research

QIS for HEP

- MAGIS-100 cold atom interferometers
- Qubit-based sensors for dark matter detection
- Dark SRF cavity-based sensors for dark photon detection
- Quantum computers to simulate HEP quantum dynamics

HEP for QIS

- Better qubits from Fermilab's expertise in superconducting devices and materials
- Ionizing radiation effects on qubits characterization leveraging Fermilab infrastructure
- Control and readout systems for quantum processors
- Picosecond synchronization for quantum communications (system now operates between FNAL and ANL)

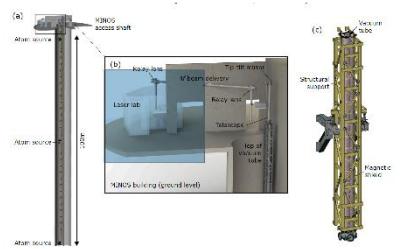
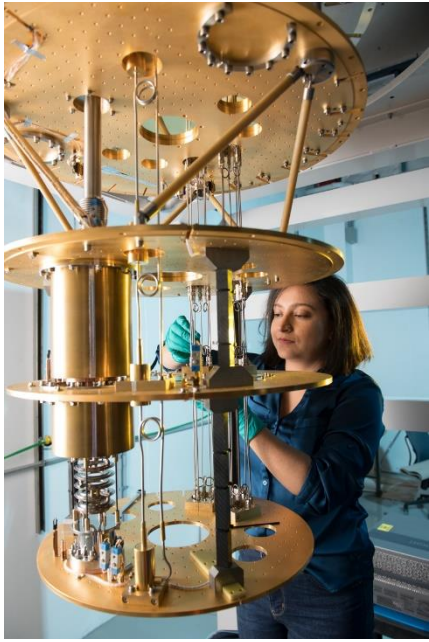


Figure 7. MAGIS-100 detector layout. (a) CAD model of the 100 m interferometer region installed



Fermilab leads one of five NQI Centers (SQMS), has a major role in the ORNL led NQI Center (QSC), and a portfolio of other QIS projects

Fermilab

Led by FNAL, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

23 Institutions
> 350 Researchers
> 100 students/postdocs

Fermilab · rigetti · Northwestern University · Ames Laboratory, Creating Materials & Energy Solutions, U.S. Department of Energy · NASA Ames Research Center

NIST · INFN Istituto Nazionale di Fisica Nucleare · Stanford University · University of Illinois Urbana-Champaign · Rutgers · Università di Pisa

University of Colorado Boulder · Illinois Institute of Technology · Johns Hopkins University · Temple University · Colorado School of Mines · The University of Arizona

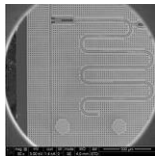
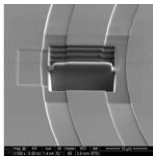
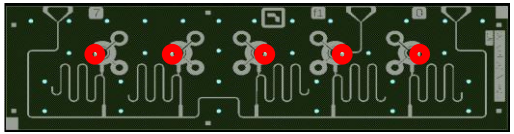
University of Minnesota · NYU · Goldman Sachs · Lockheed Martin · JANIS · Unitary Fund

Superconducting Quantum Materials and Systems Center

Develop and deploy Fermilab's first quantum computer enabled by expertise in superconducting RF technology and cryogenics, to solve pressing and currently unapproachable HEP physics problems; Demonstrate qubits of record performance with immediate tech transfer

Materials Research for Qubits

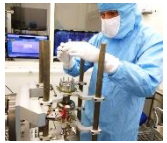
Launched multi-institutional study for material science studies towards understanding decoherence in qubits

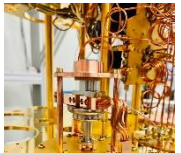




Demonstrated: new defects and interfaces in qubits causing decoherence; new material/processes for high coherence qubits

Qubit Devices and Quantum processors

Multiple quantum devices experiments ongoing: 3D SRF cavities for quantum processors, round robin experiment for planar qubits; controls and electronics development for QPUs; record size fridge



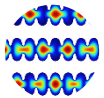



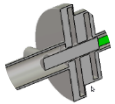
Demonstrated: record integrated cavity-qubit system for 3D quantum computing architecture

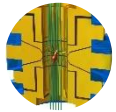
Quantum Sensing for fundamental physics

Multiple quantum sensing experiments ongoing: dark matter searches, precision measurements


DarkSRF


Multimode Cavity Axion Search

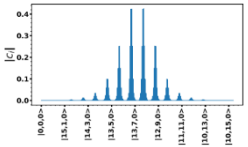

Tunable Dark Photon Search

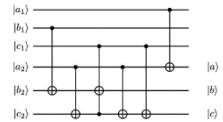

Single Particle Penning Trap

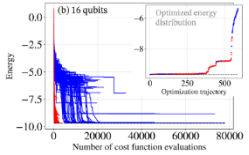
Demonstrated: most sensitive experiment for wavelike dark photons; world's record cavities quality factors for axion searches

Quantum Algorithms, Simulations, Applications

Algorithms for simulation of condensed matter/HEP theories. Engineering new and novel gates on SRF devices via strong co-design effort.


Scalar field theory simulations


Gauge theory simulations



Benchmarking condensed matter theories on real hardware

Demonstrated: new simulation algorithms for scalar field theories, gauge theories, new ways to manipulate photon states on SRF devices.

Fermilab

Fermilab AI/ML research

Fermilab has identified three focus areas where our mission needs overlap with special expertise related to AI/ML:

- “Real-time” fast AI integrated into the sensor for data-intensive HEP experiments, includes FPGAs and “AI on a chip”
- AI/ML for optimal operations of accelerators and experiments - robust real-time controls with continuous and autonomous learning and calibration systems
- Uncertainty quantification and bias; essential to get a better quantification for HEP applications such as cosmology or theory → data mapping

Nhan Tran
2019 DOE Early Career Research Award
Deep Learning Acceleration of the Boosted Higgs Program and HEP Computing

Brian Nord
2021 DOE Early Career Research Award
Simulation-based inference for cosmological parameter estimation and discovery

Alexandra Ćiprijanović
Wilson Fellow, AI/ML principal investigator

Jennifer Ngadiuba
Wilson Fellow, AI/ML principal investigator

Microelectronics and Detector R&D

Farah Fahim
2021 DOE Early Career Research Award
Front-end implementation of AI/ML neural networks for on-detector radiation-hard edge compute

Fermilab received a 2021 funding award from SC for **Microelectronics co-design research**

- Leverages and strengthens expertise in cryogenic electronics developed for DUNE
- Partnership with ORNL, BNL, 6 universities, Qualcomm, and INFN

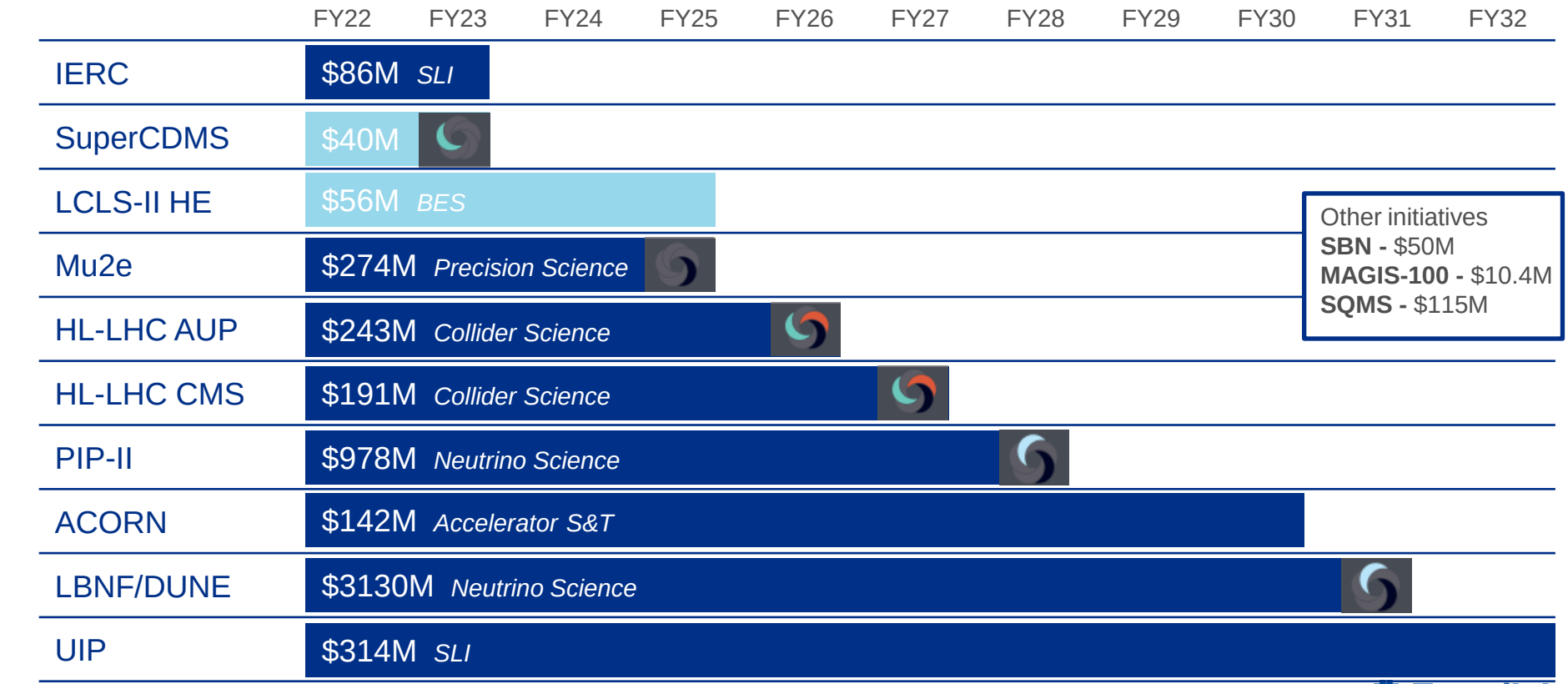
Fermilab's **Detector R&D Strategic Plan** identified two other focus areas where the lab has special expertise and facilities as well as long-term programmatic interest

- Picosecond timing for advanced particle detectors
- Advances in detectors using liquid argon/xenon

Fermilab's Test Beam Facility including the new **Irradiation Test Area** is essential for national detector R&D efforts including HL-LHC upgrade projects

Fermilab executes the P5 plan

Investment
$5.6B DOE,
$1.1B International



Other initiatives
SBN - $50M
MAGIS-100 - $10.4M
SQMS - $115M

Fermilab

Securing a vibrant future for U.S. HEP: Fermilab engages in community planning via Snowmass and next P5

- **The US Particle Physics Community Study (Snowmass), led by Fermilab distinguished scientist Joel Butler, is close to completion;** opportune time to develop US strategy for timeframe beyond LBNF/DUNE/PIP-II

July – Final meeting of the Snowmass Community Planning Exercise
September – Draft Executive Summary and Report Summary
October-November – Snowmass Book finalized as input to P5

Snowmass 2021

- **Great labwide leadership in Snowmass:** convenors, working group leaders, whitepaper contributors


Vladimir Shiltsev (FNAL)


Aaron Chou (Fermilab)


Daniel Elvira (FNAL)


Petra Merkel (FNAL)


Bob Bernstein (FNAL)

Two Fermilab working groups in preparation for the next P5

- Science Priorities Working Group, chaired by Jim Amundson
- Proton Intensity Upgrade Central Design Group, chaired by Steve Brice and Brenna Flaugher

Summary

- Our mission is strong, compelling and beautiful! Our community is world-class!
- Fermilab, along with its national & international partners, remains laser-focused on executing the P5 vision
  - LBNF/DUNE is the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy on US soil and Fermilab's highest priority
  - Through partnerships, we are building a highly capable, world leading neutrino program, which secures US leadership in a key element of the global particle physics program
- Going forward:
  - Actively involved in Snowmass toward the next P5 Plan
  - The intellectual vitality and open and inclusive culture of Fermilab are essential for the health of our field
- By defining a bold yet realistic vision and a new strategic plan, together we can ensure that US remains a global leader in High Energy Physics

We are grateful to the HEP community's commitment to the P5 vision and strong support from DOE and our International Partners

Thank you!
We look forward to welcoming you all back to Fermilab!

Wilson Hall and IERC at dawn. The sloped roof on IERC is intended to mimic the curve of Wilson Hall rotated 90 degrees; this is especially evident when the image of IERC is doubled in the reflecting pond. Photo credit: Brian Rubik