



The Fermilab Program

Lia Meringa

NuFact 2024 – The 25th International Workshop on Neutrinos from Accelerators

Argonne National Lab

16 September 2024

NuFact 2024

Lemont, Illinois, United States
September 16th - 21st, 2024

The 25th international workshop on Neutrinos from Accelerators

LOCAL ORGANIZING COMMITTEE

WORKING GROUP CONVENERS

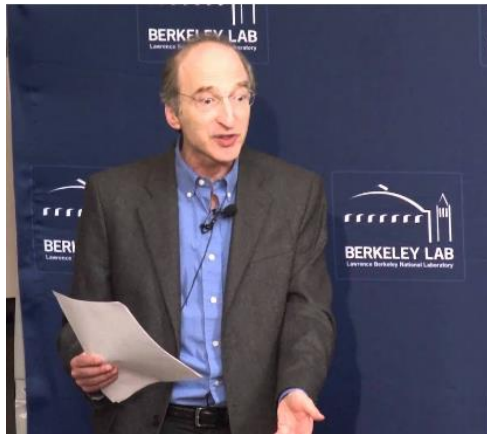
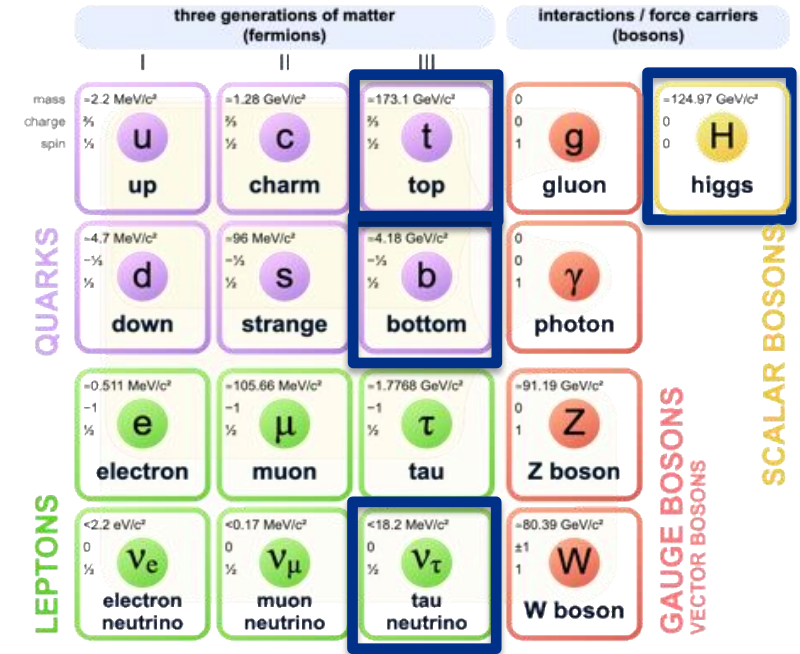
SCIENTIFIC PROGRAM COMMITTEE

Email: nufact2024@fnal.gov
 Website: <https://indico.fnal.gov/event/6340/>
KEK | **Northwestern** | **U.S. DEPARTMENT OF ENERGY** | **Argonne NATIONAL LABORATORY**
 Department of Physics and Astronomy | High Energy Accelerator Research Organization

The Triumph of the Standard Model

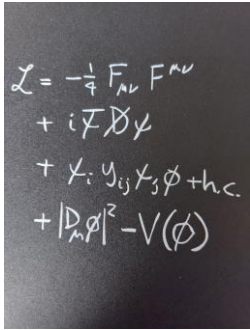
- Over the past ~50 years, particle physics has celebrated the triumph of the Standard Model with discoveries, including:
 - the top quark (heaviest elementary particle)
 - neutrino oscillations, establishing that neutrinos have mass
 - the accelerated expansion of the universe
 - the Higgs boson

Standard Model of Elementary Particles



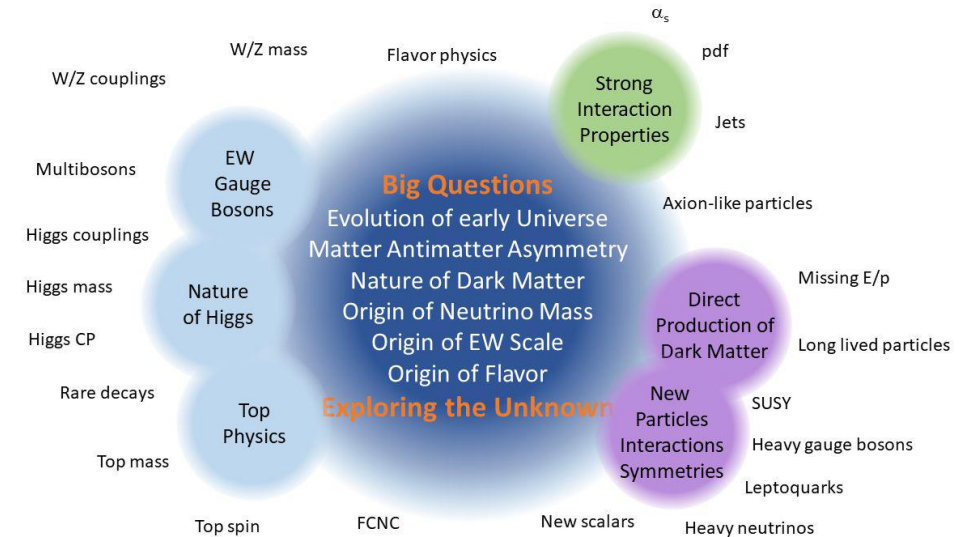
The Standard Model is incomplete

- Even though the Standard Model (SM) is currently the best description of the subatomic world, it does not explain the complete picture. Outstanding questions remain, such as:
 - What is dark matter?
 - What happened to the antimatter after the big bang?
 - What is the nature of the Higgs?
 - What is the origin of neutrino masses?
- Furthermore, there is increasing experimental evidence of deviations from the SM. For example:
 - Muon g-2 tension
 - Short baseline neutrino anomalies
- Perhaps, the Standard Model is only a part of a bigger picture that includes new physics...

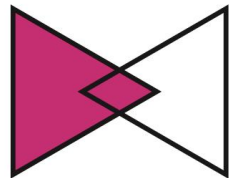
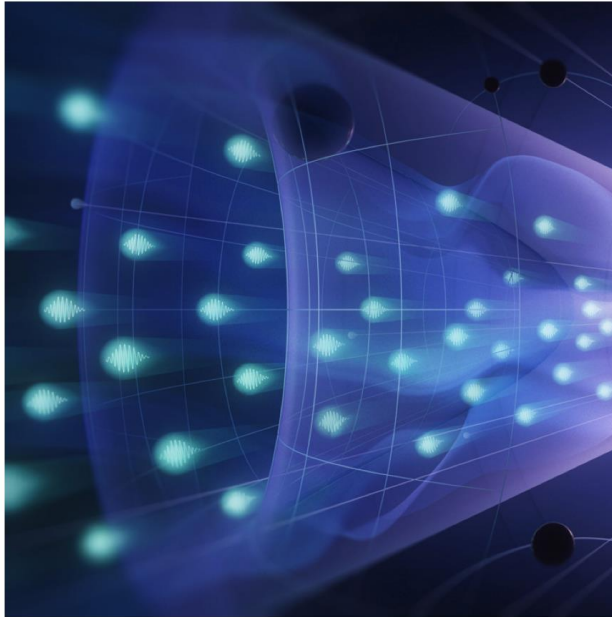

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi}\not{D}\psi \\ & + \bar{\psi}_i \gamma_{ij} \psi_j \phi + h.c. \\ & + |D_{\mu}\phi|^2 - V(\phi) \end{aligned}$$

Profound Particle Physics questions with great discovery potential

- Physics associated with neutrinos
 - Matter-antimatter asymmetry
- Nature of the Higgs boson
 - How does everything acquire mass?
- Nature of Dark Matter
 - Where is 85% of the matter of the universe?
- Understanding cosmic acceleration
 - Dark energy and inflation
- Physics beyond the Standard Model
 - New particles, interactions, symmetries, quantum gravity



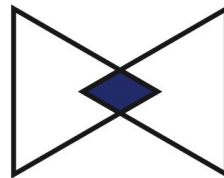
2023 P5 Science Drivers



Decipher
the
Quantum
Realm

Elucidate the Mysteries
of Neutrinos

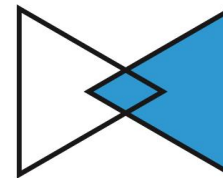
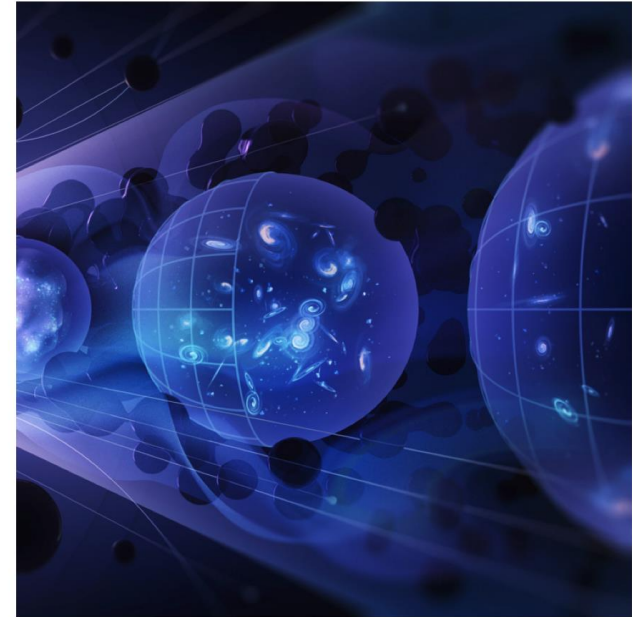
Reveal the Secrets of
the Higgs Boson



Explore
New
Paradigms
in Physics

Search for Direct Evidence
of New Particles

Pursue Quantum Imprints
of New Phenomena



Illuminate
the
Hidden
Universe

Determine the Nature
of Dark Matter

Understand What Drives
Cosmic Evolution

Significant advances in technology and enabling R&D

- Accelerator Science & Technology
- Detectors/Instrumentation
- Computing
- Artificial Intelligence
- Quantum Information Science & Technology
- Microelectronics

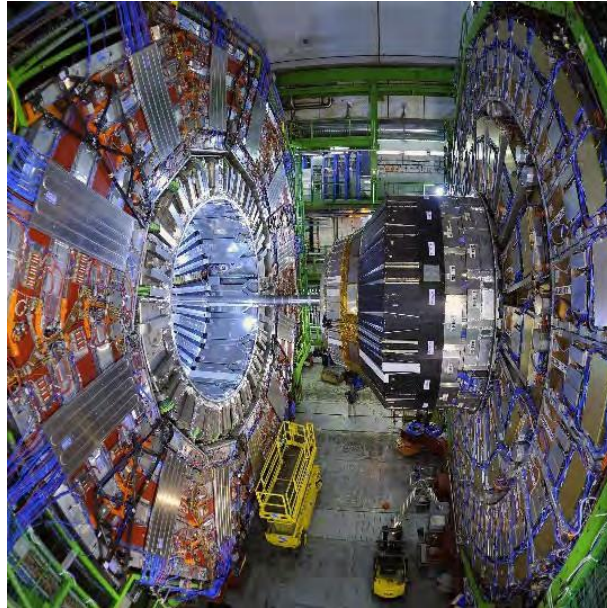
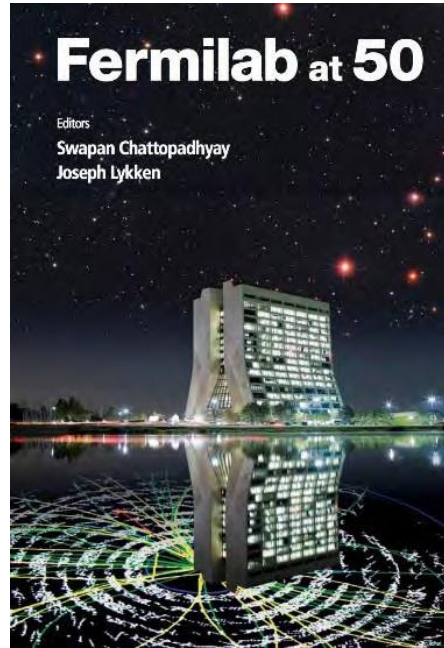
This is a defining moment for the field and for Fermilab

Fermilab at a glance

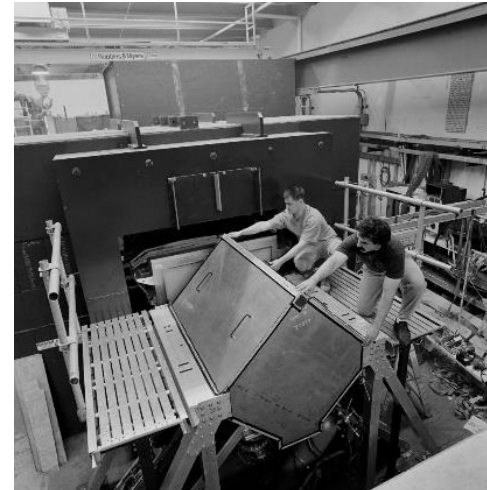
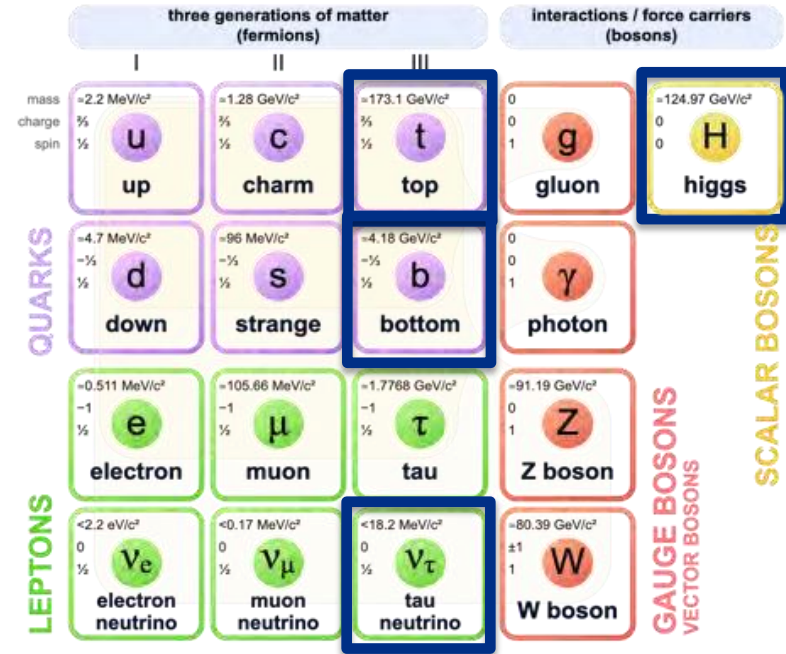
- America's particle physics and accelerator laboratory
- Operates the largest U.S. particle accelerator complex
- ~2,100 staff and
- 6,800 acres of federal land
- Facilities used by 4,000 scientists from >50 countries
- As we move into the next 50 years, our mission remains to solve the mysteries of matter, energy, space, and time for the benefit of all.



55 years of discovery



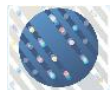
Standard Model of Elementary Particles



Fermilab Science Mission enables 2014 and 2023 P5 plans



Higgs boson



Neutrinos



Dark matter

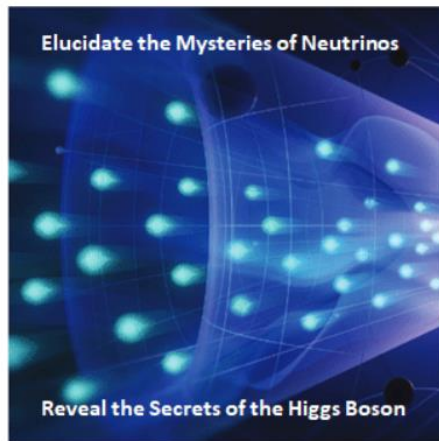


Dark energy and inflation



Exploring the unknown

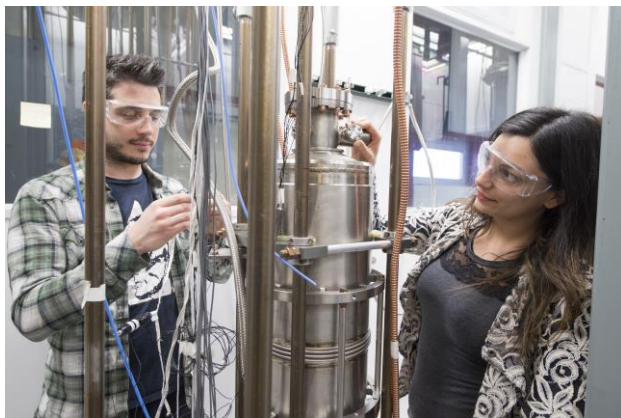
Decipher the Quantum Realm



Explore New Paradigms of Physics



Illuminate the Hidden Universe



Fermilab is delivering on the DOE/SC discovery science mission: Major particle physics breakthroughs from Fermilab experiments, major technology breakthroughs from Fermilab research



Fermilab Science and Technology Strategy

Major Particle Physics Initiatives

- Neutrinos
- Higgs and the Energy Frontier
- Muons
- The Dark Universe
- Accelerator Science and Technology



Emerging Technology Initiatives

- Quantum Science and Technology
- Microelectronics
- Artificial Intelligence for Science

User and Stakeholder Engagement Initiative

- Discovery on the Prairie



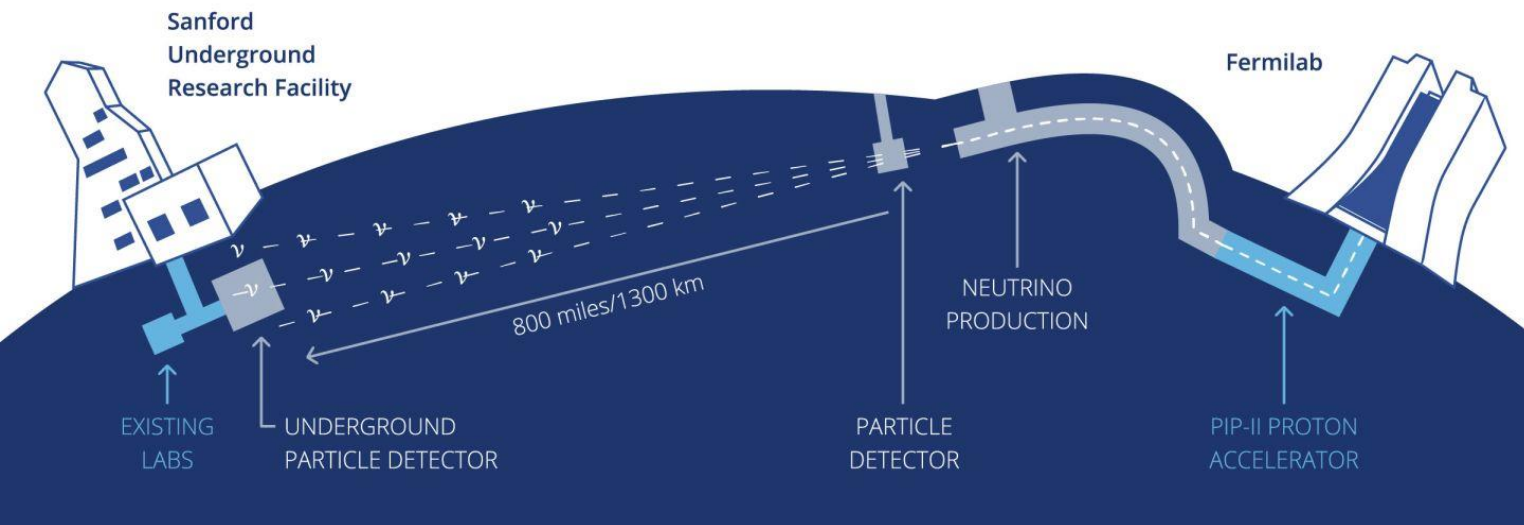


The *definitive* neutrino oscillation experiment, driven by LBNF and PIP-II



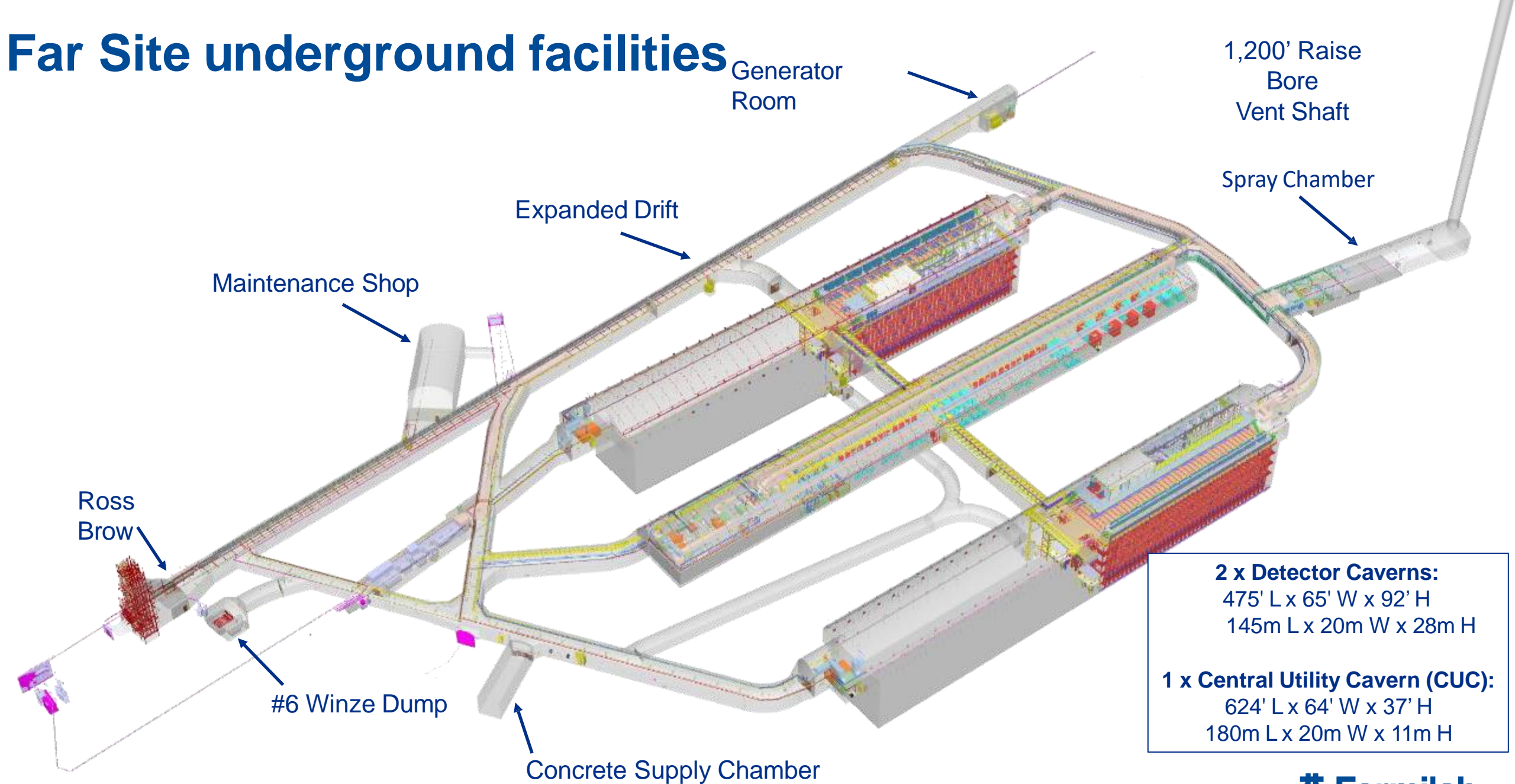
Discovery Potential

- **Neutrino CP violation**
 - The origin of matter in the universe
- **Supernova neutrinos**
 - Origins of neutron stars and black holes
- **Neutrino surprises**
 - New forces, particles, or laws of nature connected to neutrinos
- **Proton decay**
 - Unified origins of particles and forces



The LBNF/DUNE project is the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy on U.S. soil

Far Site underground facilities



2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m W x 28m H

1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H



Far Site excavation completed 2024



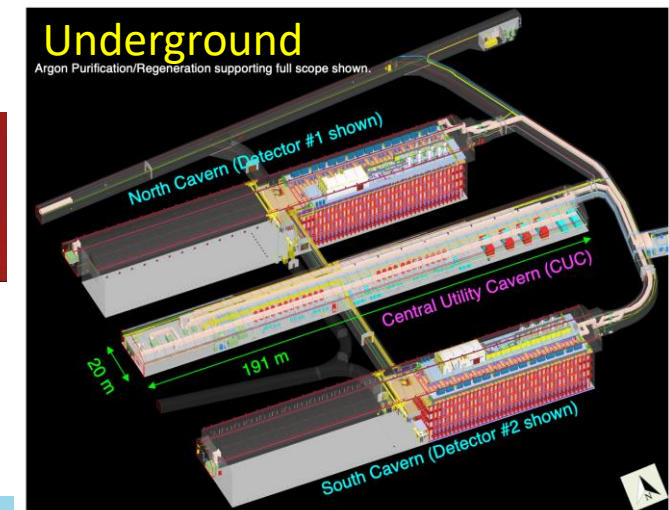
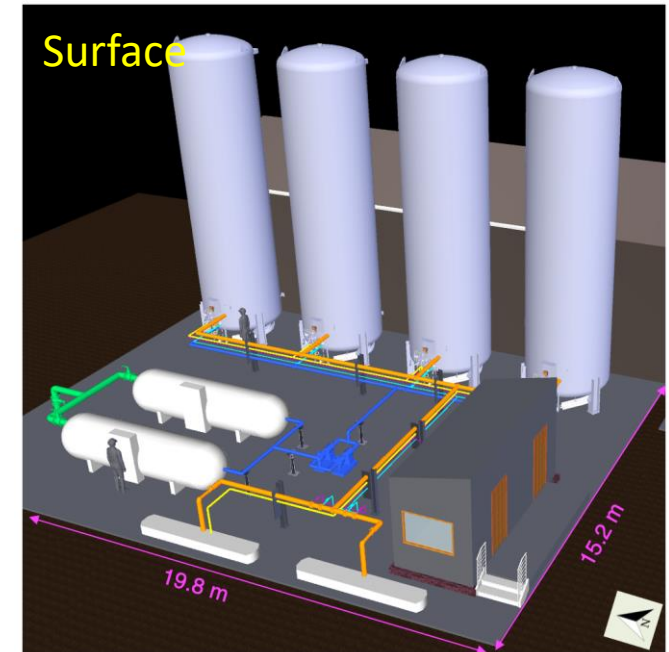
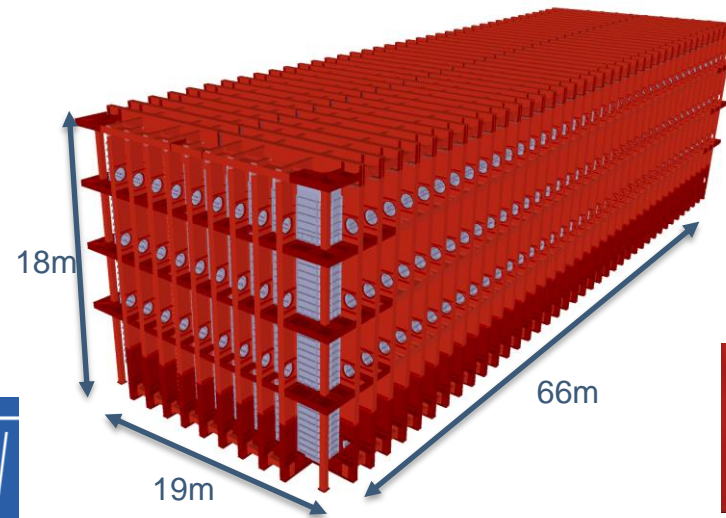
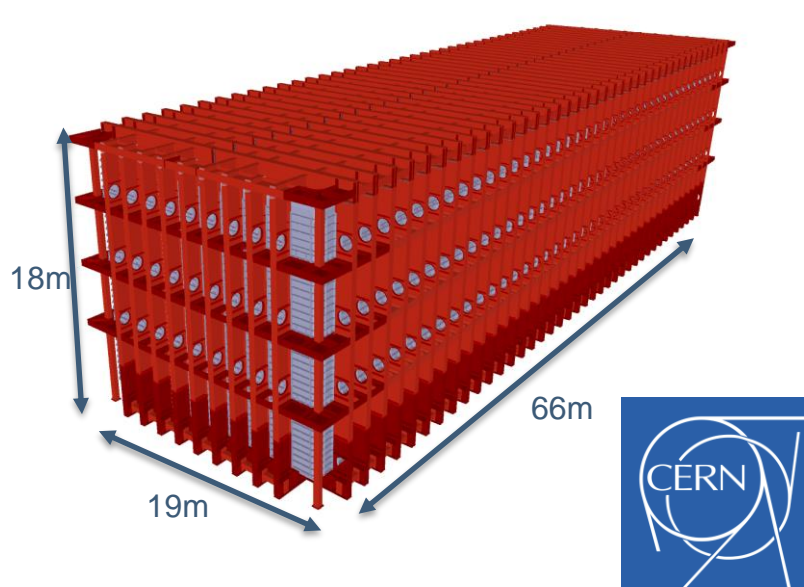
Celebrating the completion of the Far Site excavation



The Far Site Facility – Includes significant in-kind contributions

The far site facility includes

- 3 caverns
- 2 cryostats
- 2 detectors
- Cryogenic infrastructure



Delivery of LBNF hardware components by CERN has begun

Far Detector and Cryogenic Infrastructure

- Cryostat Steel being completed / prepped for shipment
- *QC of all aspects of shipping – components, packing materials, safe shipment – is critical to overall success*

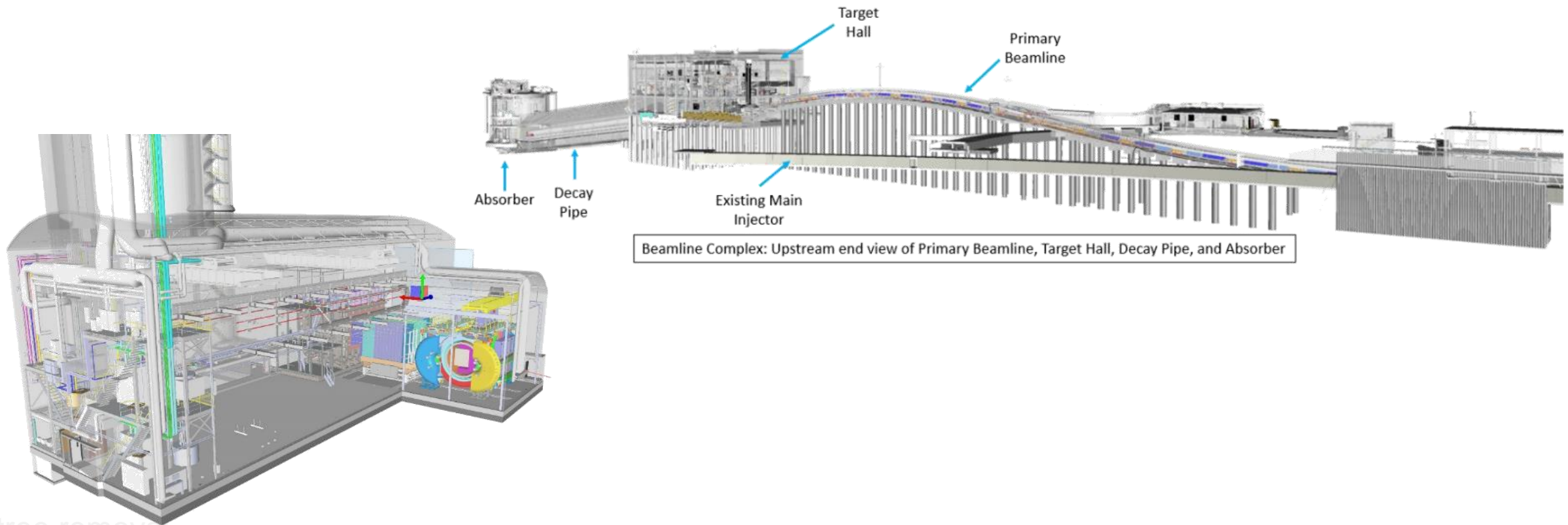


Make No Little Plans



Near Site Conventional Facilities / Beamline Sub Projects

- RFPs out for bid for Beamline Complex and Near Detector Complex construction contracts
 - Multiple interested companies attended information meetings
- Beamline Design Report reviewed and complete



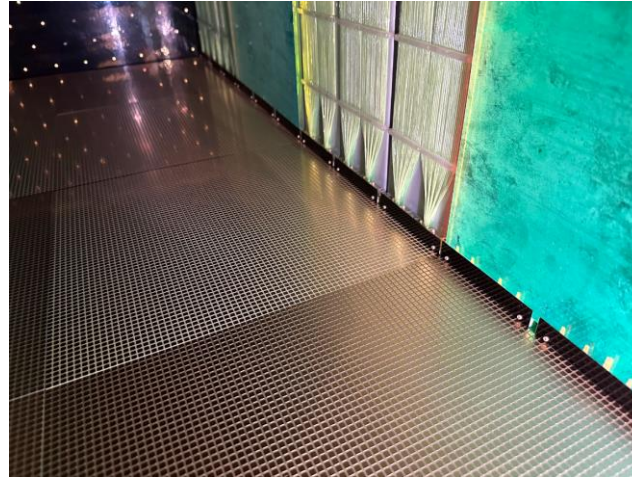
tree removal

2x2 demonstrator for the DUNE Near Detector ND-LAr

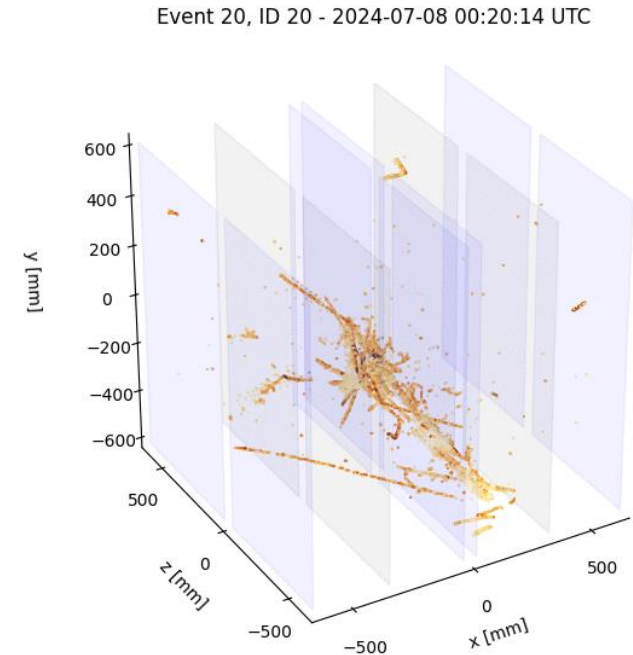
- Physics performance demonstration
 - Study the highly complex topologies and pileup that we expect at DUNE
- In the NuMI neutrino beam line at Fermilab
- First neutrinos observed with a DUNE prototype July 2024



4 modules of the 2x2 hanging above the cryostat during installation

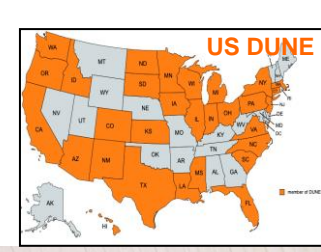


Pixelated readout



First neutrino interactions recorded on July 7th and 8th

DUNE International Collaboration hosted by Fermilab



DUNE Collaboration meeting at Fermilab - May 2023

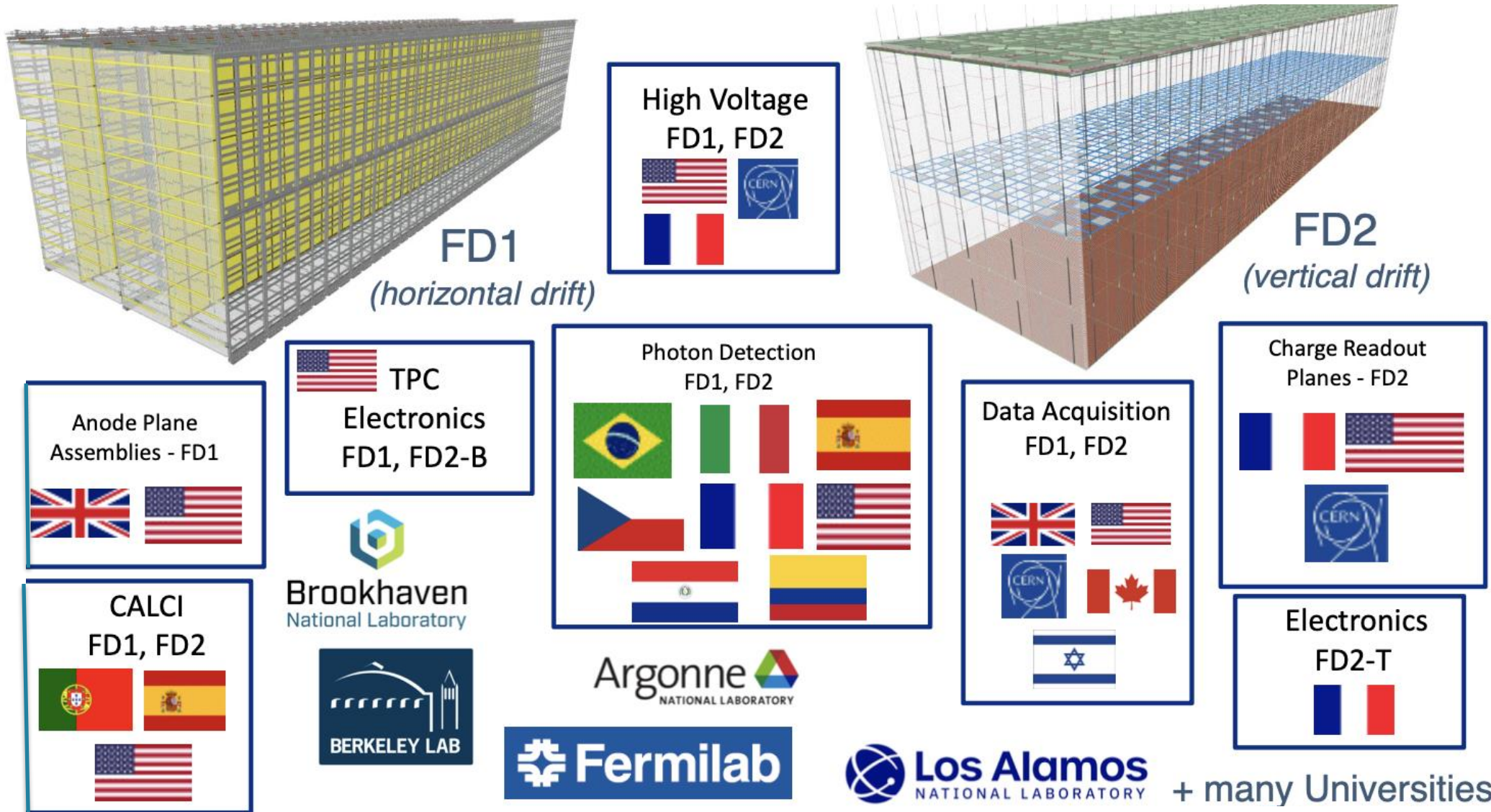
- DUNE collaboration comprises 1400 scientists and engineers at about 200 institutions
 - About 50% at U.S. institutions, 50% abroad (35 countries)
 - 350 students, 250 postdocs
- Fermilab is the host lab of DUNE: Established the **DUNE Coordination Office** in May 2023

DUNE Partners sign multi-institutional MOU

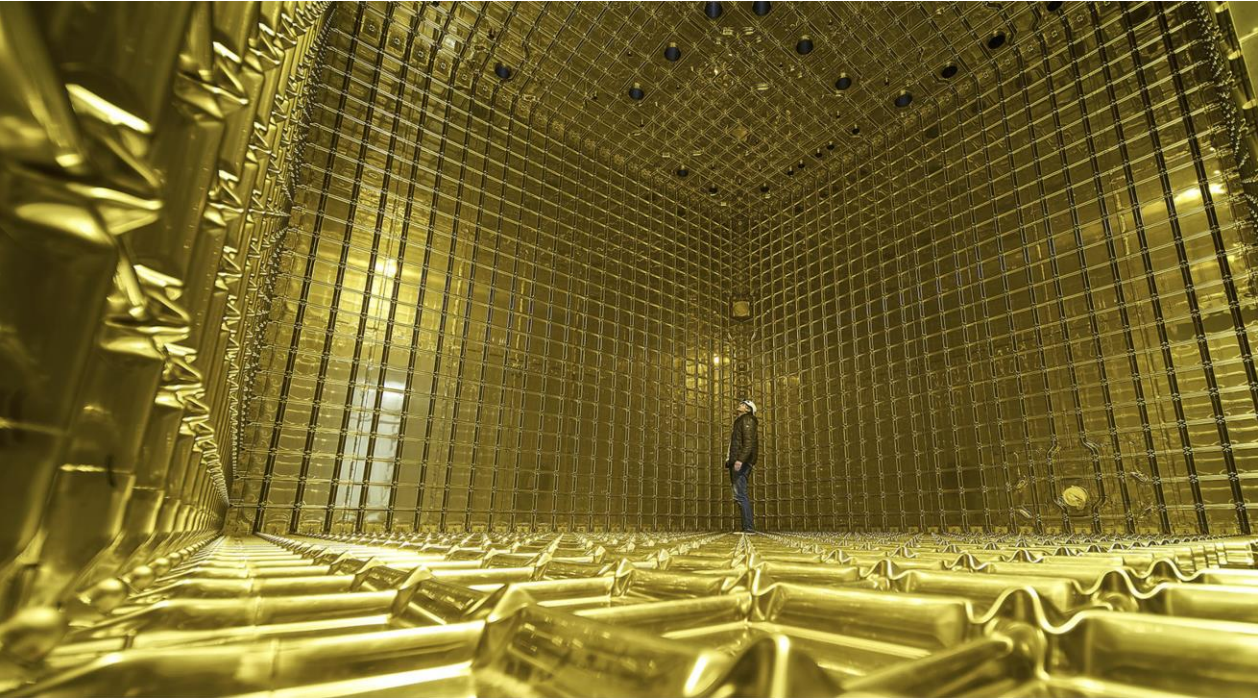
- International science organizations sign agreement to provide hardware for the Deep Underground Neutrino Experiment



The DUNE Far Detectors – A Model of International Partnership



ProtoDUNE Detectors (Far Detectors 1 and 2) at CERN



CERN Neutrino Platform: first time CERN invests outside Europe

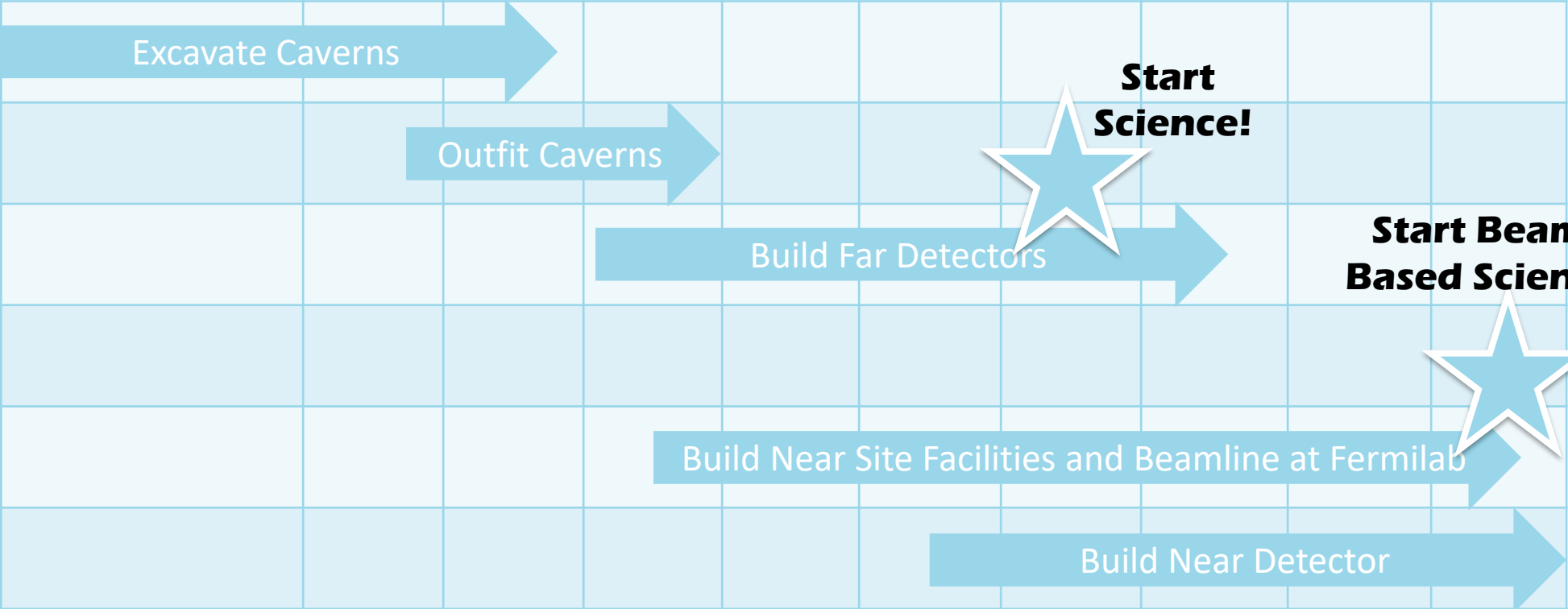


Cost & Schedule Summary

LBNF/DUNE-US Cost
\$3,277M

LBNF/DUNE-US Project Funding Profile (\$M) / Schedule

Thru 2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	Total
\$955	\$180	\$255	\$280	\$305	\$305	\$305	\$305	\$262	\$0	\$3,277



Jim Kerby
LBNF/DUNE-US
Project Director

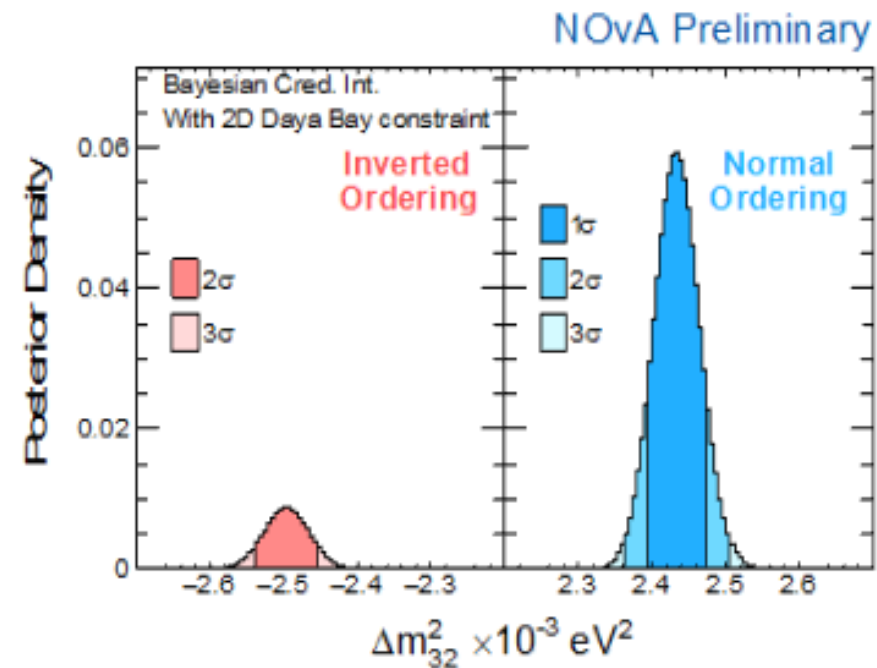
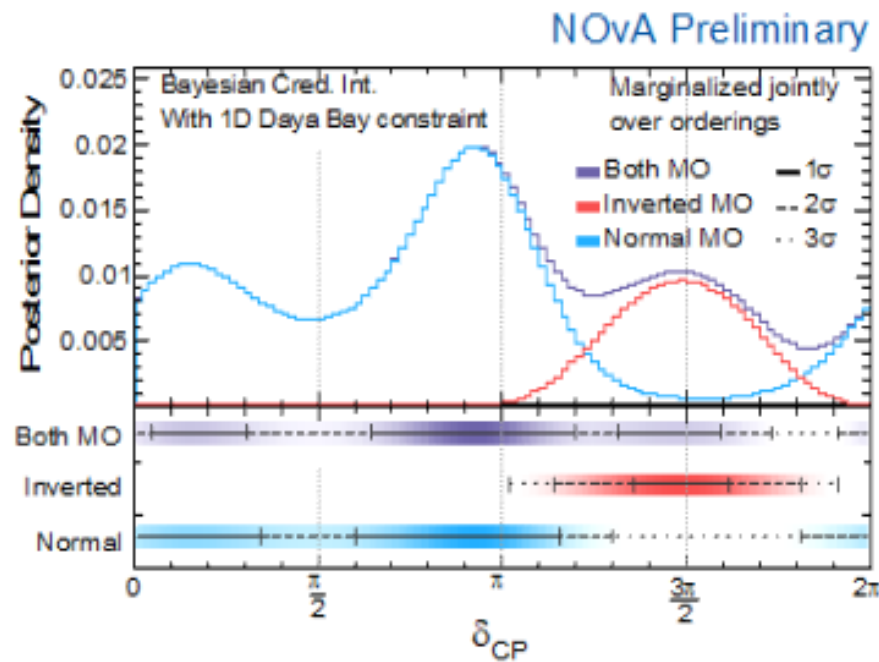
LBNF /DUNE is the largest domestic project in DOE Office of Science

The LBNF/DUNE vision is achieved by groundbreaking international partnerships

- The U.S. is a partner of choice in international science
- For the first time the U.S. is executing and hosting an international experiment
- For the first time CERN contributes to infrastructure outside Europe
- Partner contributions total more than \$1B



Mass Ordering and CP Results



Normal MO: data prefer CP-conserving δ_{CP} values
 Inverted MO: data prefer maximal CP-violation,
 $\delta_{CP}=0,\pi$ not in 3 σ allowed interval

Frequentist best fit:

Normal ordering, Upper Octant

$$\delta_{CP} = 0.875\pi$$

Using Daya Bay to constrain both θ_{13} and Δm^2 , NOvA data favor Normal MO by $\sim 7:1$ odds (Bayes factor of 6.8).

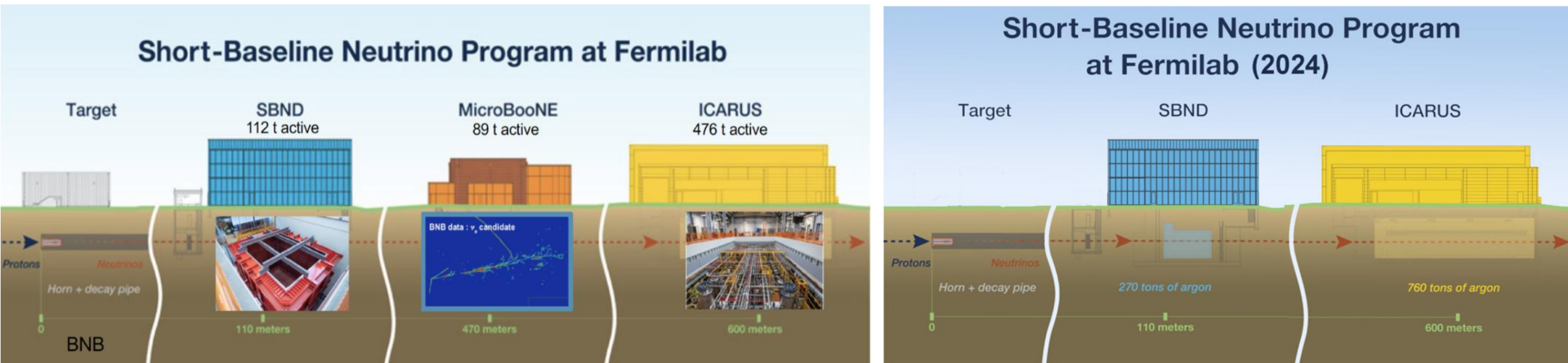
Frequentist fit disfavors Inverted MO at 1.6 σ

Short Baseline Neutrino (SBN) program

Science target: resolve the SBN anomalies with the possibility of discovering sterile neutrinos or other exotic neutrino physics

The SBN program is a 2014 P5 report recommendation: Pursue an exciting accelerator-based short baseline neutrino program at Fermilab

- 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 era



Short Baseline Neutrino Detector (SBND) Experiment

SBND is the near detector in the Short-Baseline Neutrino Program

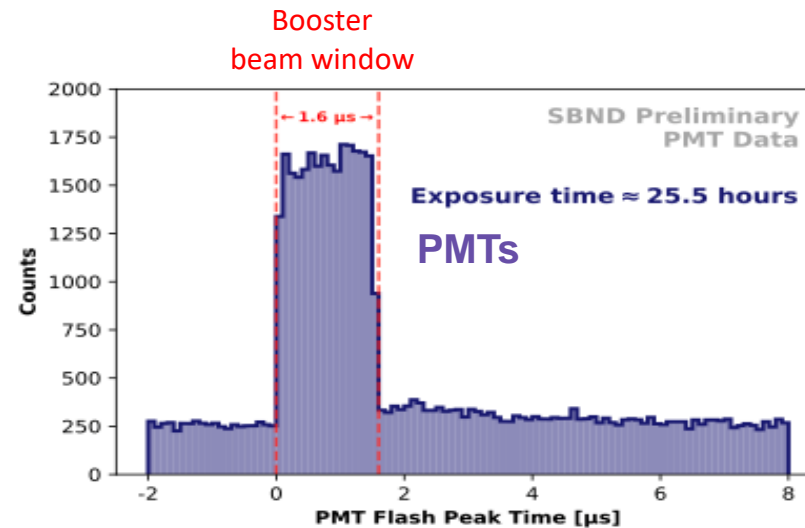
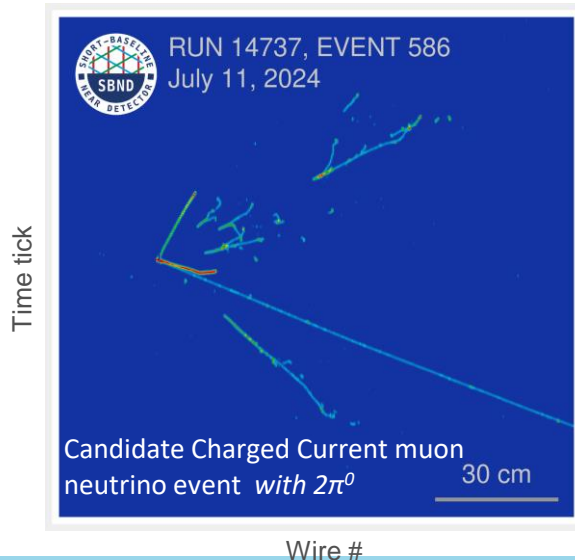
- The SBND detector is fully operational since July 3, 2024.
- SBND collected a week of BNB neutrino in July 2024 and continued running through the summer (collecting cosmics).
 - A week of SBND running = tens of thousands of neutrinos.
- Between now and the start of the Fermilab long-shutdown in early 2028, SBND stands to collect 5-10M neutrino interactions (depending on beam delivery), an order of magnitude more than the existing neutrino-argon data sets.



CERN Neutrino Platform



collection plane, zoomed



The PIP-II Project at Fermilab



Pantaleo Raimondi
PIP-II Project
Director

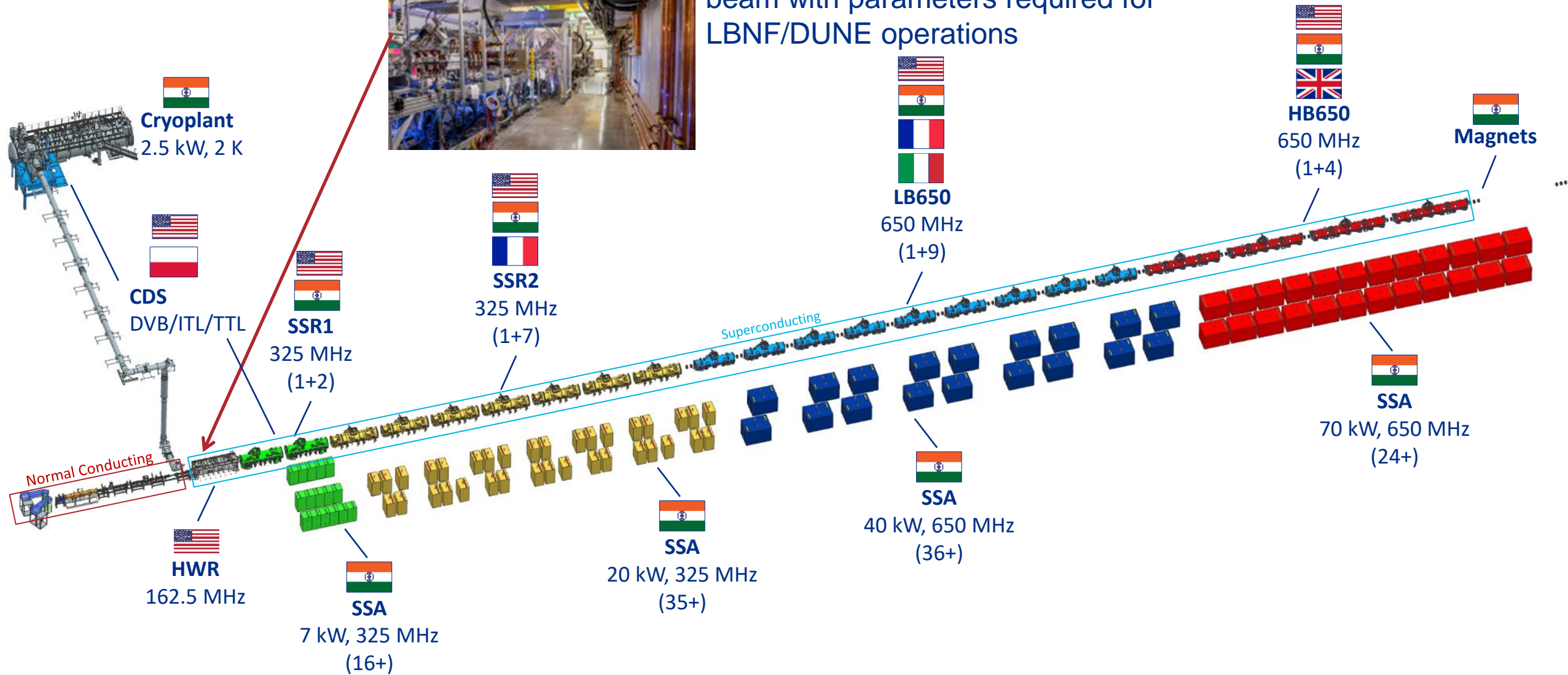


PIP-II is an essential upgrade to Fermilab accelerator complex to enable powerful, wideband neutrino beam to LBNF/DUNE, and a broad physics research program for decades to come

SRF Linac



PIP2IT successfully demonstrated 17 MeV beam with parameters required for LBNF/DUNE operations



Prototype SRF Cryomodules



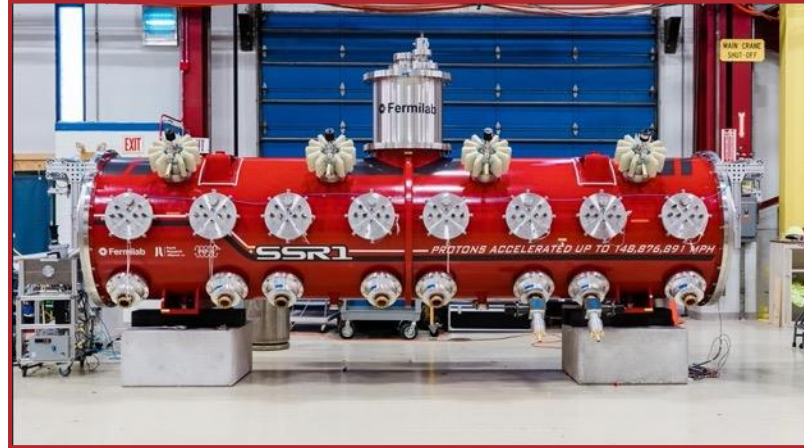
Prototype HWR Cryomodule



- 2K Static Heat Load: 44W
- LINAC ready after minor repairs



Prototype SSR1 Cryomodule



- 2K Static Heat Load: 32 W
- LINAC ready after interfaces reconfiguration

Prototype HB650 Cryomodule



- 2K Static Heat Load: 27.5 W
- Is being rebuilt

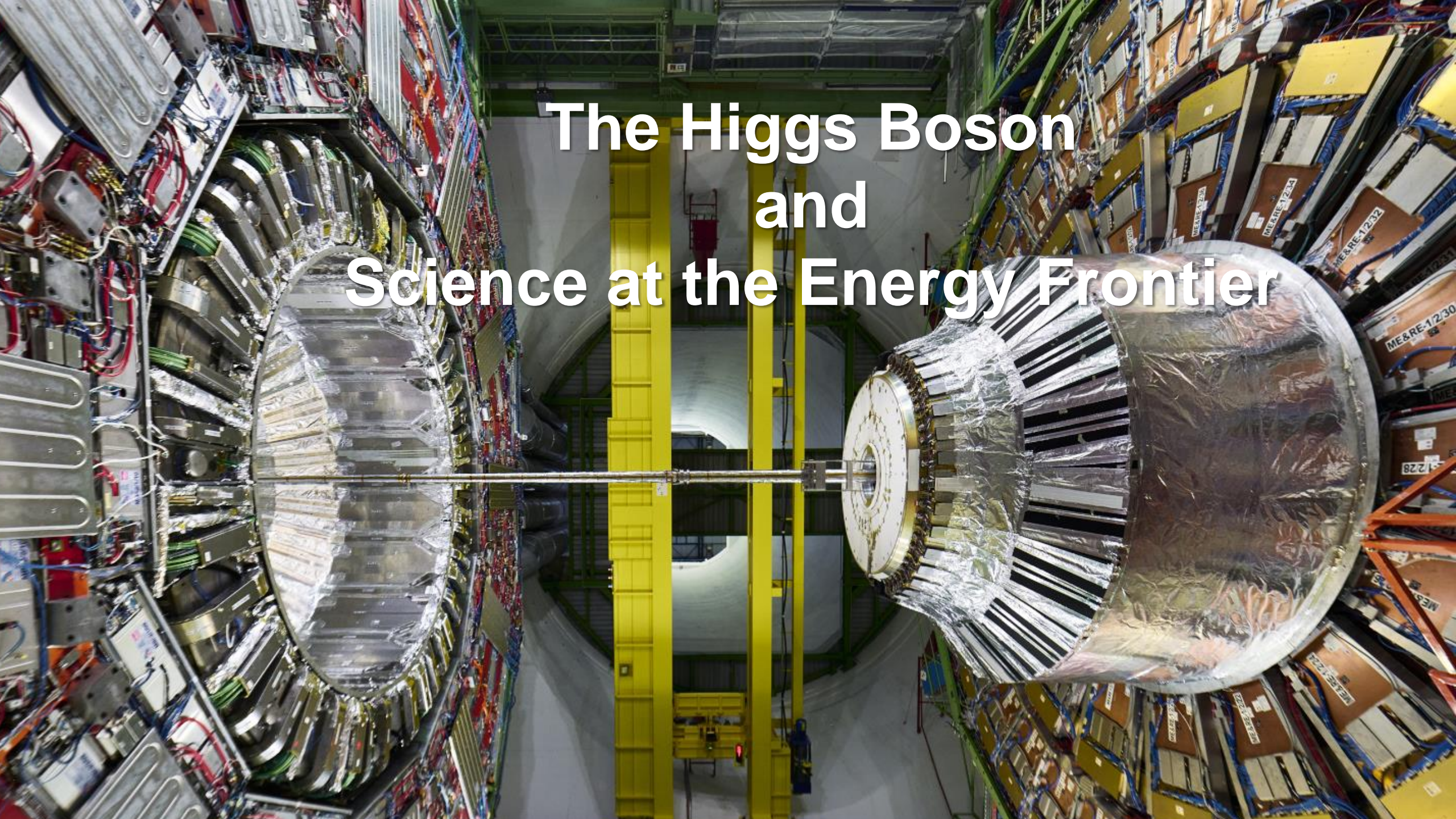
The HWR, SSR1, and HB650 prototype cryomodules provided critical results, increasing the chances of success in the production phase

Conventional Facilities

SRF Linac and Transfer Line Tunnel construction is on schedule and will be completed by Feb 2026



The Higgs Boson and Science at the Energy Frontier





Higgs and Energy Frontier



Vision: Fermilab is the leading U.S. center for CMS and second leading center in the world after our partner CERN, and has leadership roles in off-shore Higgs Factory R&D

Major initiatives

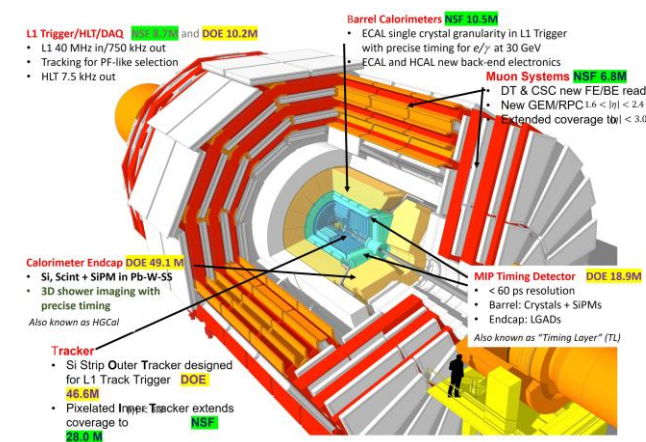
- LHC CMS operations
- HL-LHC AUP and CMS Detector Upgrade Projects
- FCC-ee accelerator & detector R&D



LHC Remote Operations Center (ROC) at Fermilab
CMS online shifts



HL-LHC AUP 1st CryoAssembly at Fermilab



HL-LHC CMS scope



Higgs and Energy Frontier

HL-LHC Upgrade Projects

- First U.S.-built cryoassembly for LHC upgrade shipped to CERN
 - On Dec. 18, CERN (Switzerland) received a 13-meter-long magnet assembly
- HL-LHC CMS Detector Upgrade Project achieved CD-3 ESAAB!

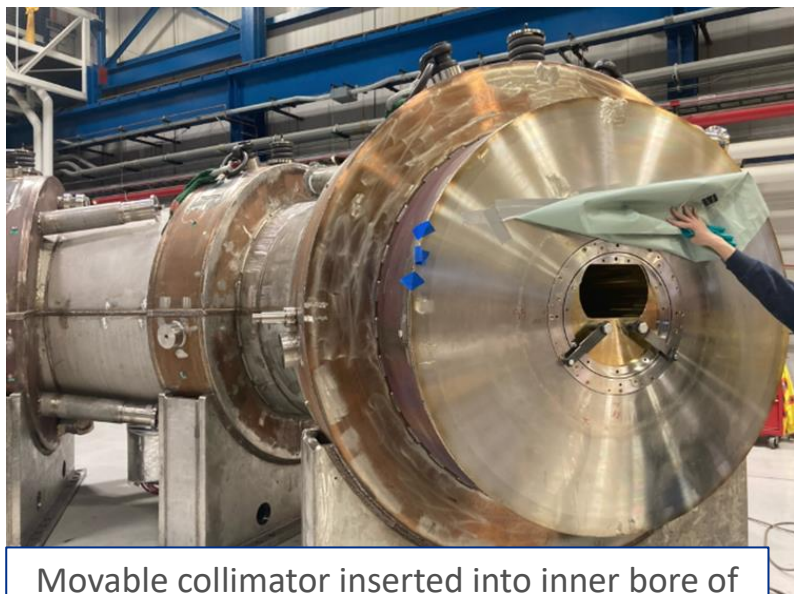


Muons

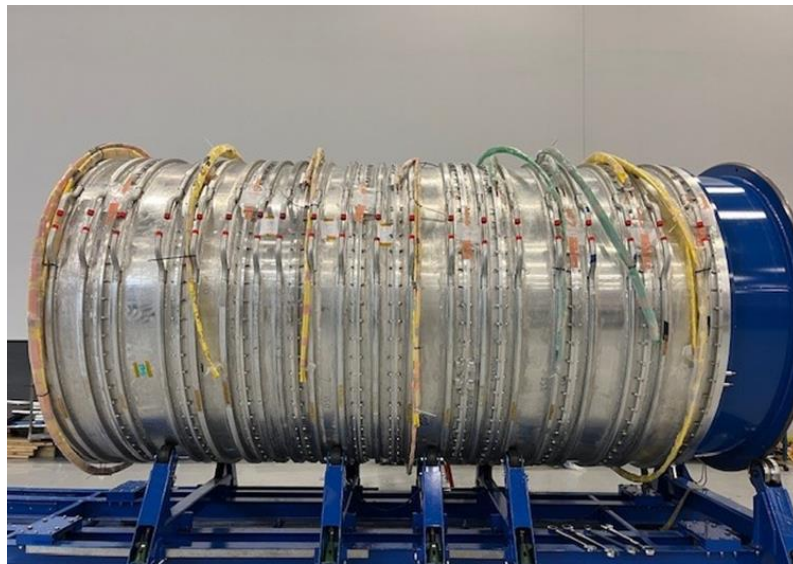
Vision: Fermilab is a world center for accelerator-based Charged-lepton flavor violation (CLFV) and Dark Matter experiments, driven by intense particles beams and PIP-II/ACE

Major initiatives

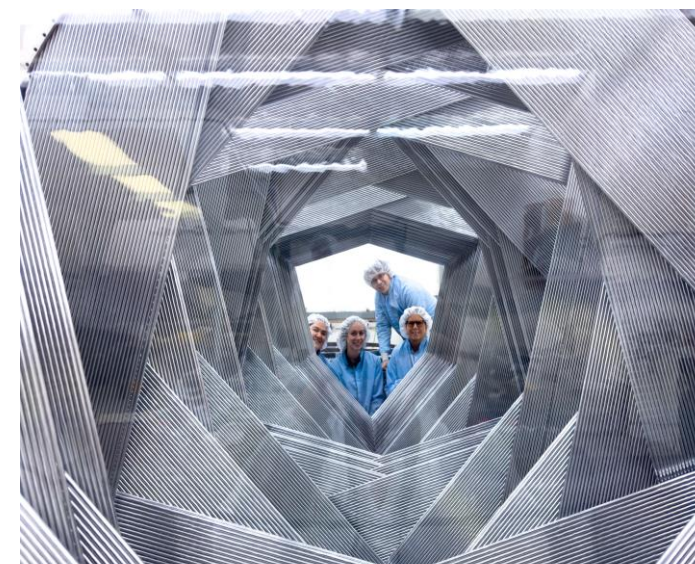
- **Muon g-2:** Data taking concluded, statistics goal achieved!
- **Mu2e project:** Project under construction ~91% complete, start science in 2026



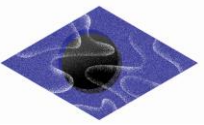
Movable collimator inserted into inner bore of downstream Transport Solenoid



Detector Solenoid in progress



Tracker plane assembly



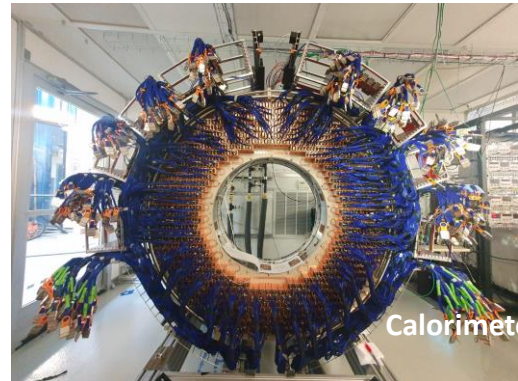
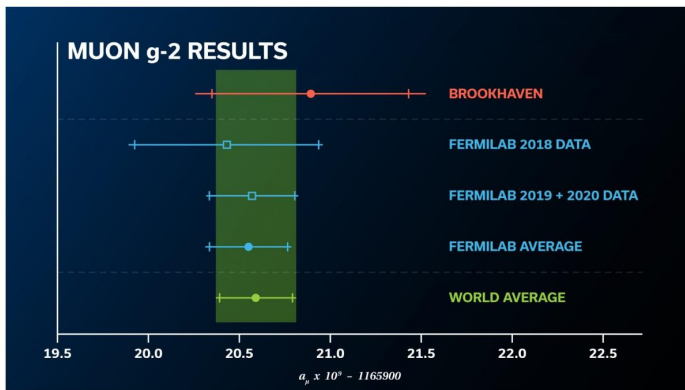
Muons: FY24 Major Accomplishments

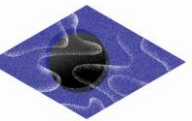
Mu2e

- Mu2e Project is 91% complete
- Two transport solenoids were safely delivered to the Mu2e experimental hall
- First cryogenics delivered to Mu2e building
- Tracker plane assembly 92% complete - Electronics installation progressing

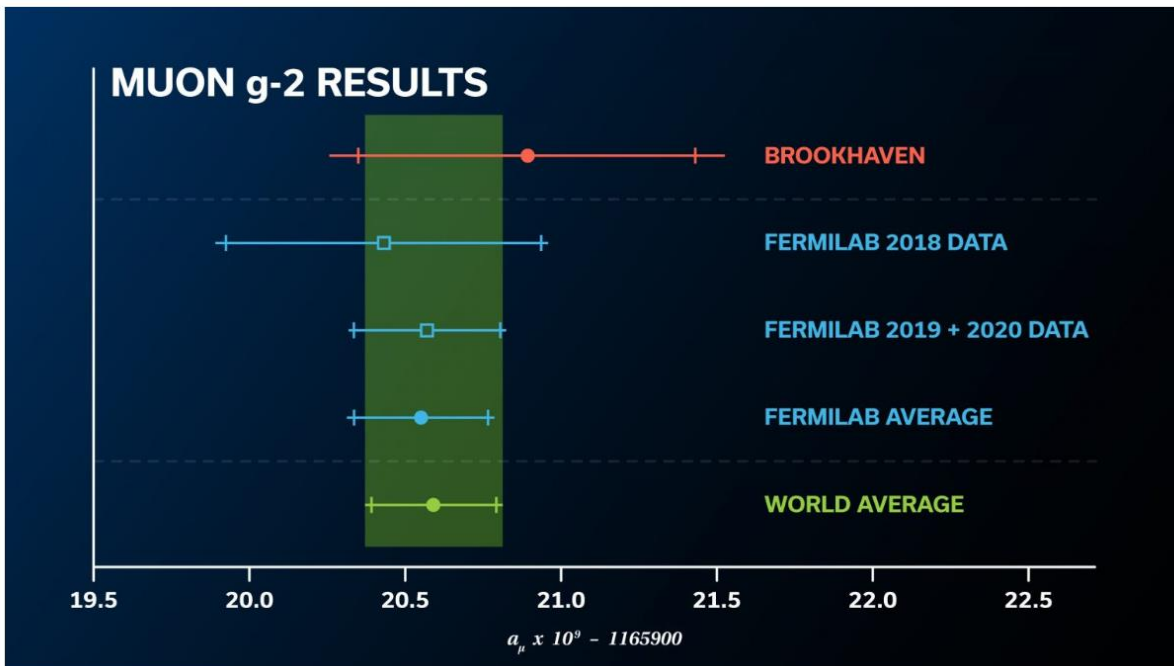
Muon g-2

- Achieved statistics goals
- World's most precise measurement of muon g-2 was released in August
- Final result, updates from Theory Initiative expected in 2025 timescale





Muon g-2 achieves unprecedented precision!



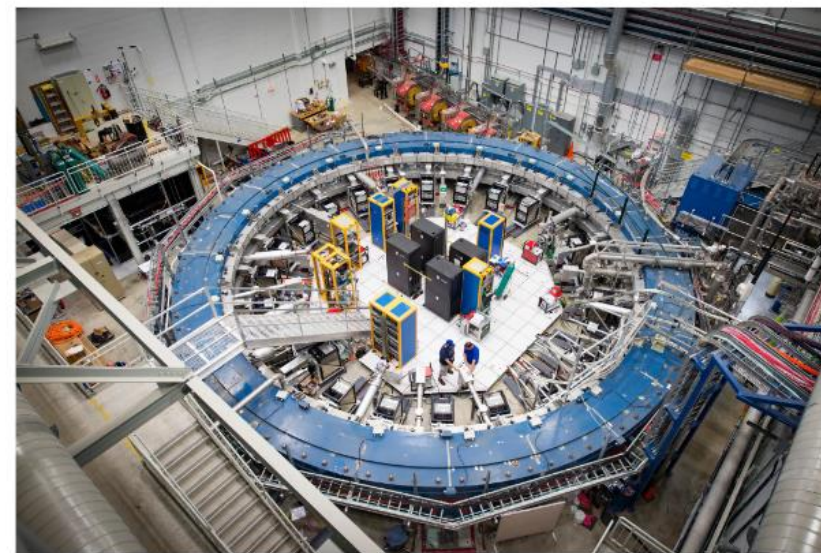
The Muon g-2 collaboration achieved the world's most precise measurement of the anomalous magnetic moment of the muon!

The New York Times

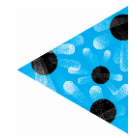
Physicists Move One Step Closer to a Theoretical Showdown

The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.

Share full article | 480



The Muon g-2 ring at the Fermilab particle accelerator complex in Batavia, Ill. Reidar Hahn/Fermilab, via US Department of Energy



Dark Universe

Vision: Fermilab is an essential partner in cosmic science experiments and is contributing innovative R&D efforts toward future dark energy, dark matter, and cosmic microwave background (CMB) experiments.

Strategy:

- Search for dark matter across a wide mass range leveraging Fermilab's instrumentation facilities/capabilities
- Support the advancement of CMB experiments while playing key roles in current and upcoming surveys to study cosmic acceleration

Priorities:

- Support current operations: Rubin/LSST, SPT-3G, SCDMS
- ADMX-G2: Continue run searching for the QCD axion
- Dark Matter New Initiatives (DMNI)



South Pole Telescope during 2022 Austral winter survey observations
(Credit: Aman Chokshi)

Accelerator S&T – World-leading Capabilities

Fermilab is addressing the needs of many SC programs

BES

FES

NP

ASCR

Accelerator and Beam Physics

- IOTA/FAST beam-test facility advances critical R&D enabling next-gen accelerators for DOE/SC

Superconducting Radio-frequency

- Fermilab continues to produce world-class cryomodules for LCLS-II HE, PIP-II, applying developments to FCC-ee

High-power Targetry

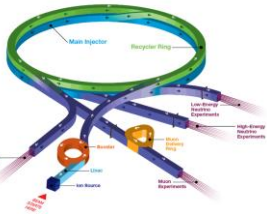
- Fermilab leads the Radiation Damage in Accelerator Target Environments (RaDIATE) collaboration

High-field Magnets

- HEP and FES: New high field magnet cryogenic test stand at Fermilab to perform R&D of high-temp superconducting cables for future fusion reactors

Fermilab Accelerator Complex Evolution (ACE)

Fermilab Accelerator Complex



Accelerator Complex

Campaign of upgrades, modernization, investments critical for the success of DUNE

PIP-II Project

Other projects, e.g. ACORN, to ensure accelerator complex is compatible with PIP-II

ACE-MIRT

Faster delivery of DUNE science: capability \times capacity \times reliability

20-year strategic plan

ACE-BR, Muon Collider



**Deliver
groundbreaking
science & technology
innovation**

Emerging Technologies/ National Initiatives

- Quantum Science and Technology
- Microelectronics
- Artificial Intelligence for Science



Emerging Science & Technology Initiatives

Quantum Information Science

Fermilab is pursuing a multi-pronged and vibrant QIS&T program:

- Lead **SQMS** - 1/5 DOE National QIS Centers
- Strong participation at QSC
- Broad research program aiming to enable HEP science and advance QIS&T. Our approach:
 - Quantum sensors; systems; simulation; computing

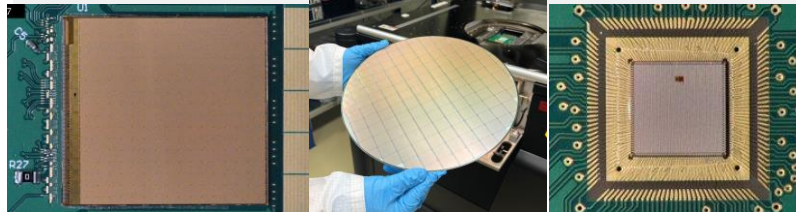


Microelectronics

HEP experiments set the grand challenge for enabling next generation microelectronics.

Our vision is to leverage our core capabilities while working with academia and industry to develop microelectronics to meet our scientific goals and achieve societal impact through disruptive technologies. Our approach:

- Integrated precision sensing with computing and communication technologies
- Impactful hardware development for Quantum, AI at the edge, 6G and beyond
- Microelectronics workforce
- Support and develop US-based advance manufacturing technology

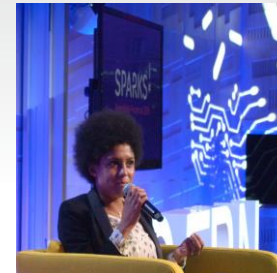


Artificial Intelligence

Unique HEP challenges will spur innovation in AI techniques and technology that will **transform HEP and advance discoveries in other sciences, society, industry.**

Major synergy with our strength in microelectronics and with the upgrade of the accelerator complex

- **Accelerators**
- **Experiments**
 - AI-enabled automation/optimization
 - Experiment design
 - Readout and control
 - Data processing and simulation
 - Automated data mining, analysis, and interpretation



User and Stakeholder Initiative: Discovery on the Prairie



Partnerships are Central to Mission Success



Lia Meringa and Mark Thomson, executive chair of the Science and Technology Facilities Council, U.K. Research and Innovation, sign a certificate to commemorate the international cooperative research and development agreement that fortifies R&D and experimental activities among Fermilab and U.K. institutions for the MAGIS-100 experiment.



Lia Meringa and xLight, Inc. CEO Nicholas Kelez shake hands to solidify a new partnership that will transition technologies developed at Fermilab for commercial applications.



Fermilab's Office of Education and Public Engagement hosted the 2023 Outdoor Family Fair, which brought the public to the lab to enjoy educational activities about its science, including the popular Mr. Freeze cryogenic show, and get a close look at Fermilab's diverse site.

International

- HEP science is driven through broad multi-national collaborations
- Major in-kind contributions critical to flagship projects

National

- Expansive university engagement, including MSIs, builds a future workforce
- Industry engagement supports U.S. competitiveness

Regional

- Support economic development initiatives
- Chicagoland as a quantum technology hub
- STEM Outreach – Lederman Science Center, Saturday Morning Physics, etc. teach and inspire educators and the next generations

Discovery on the Prairie

An integrated, long-term vision for Fermilab that expands our impact for the nation, high-energy physics, and our state and local communities

Plan

- Revitalization of campus and infrastructure driven by community needs in the DUNE era
 - Reimagined Fermilab Village
 - Phase-I housing development - \$30M investment from State of IL
 - Modern daycare, recreational and community amenities
 - A new, world-class STEM and community-outreach facility
- Technology and Innovation Park with university and industrial partners for maximizing Fermilab's impact in science, society and industry



Fermilab hosts 235 Interns this summer!



Fermilab hosting summer internship pipeline programs for 50+ years
INFO: <https://internships.fnal.gov/>

Summary

- The questions of our field are profound, the tools are exquisite, our mission is compelling and beautiful, our community is world-class
 - Together with our partners, we are advancing some of the most challenging projects ever
 - Success of the LBNF-DUNE enterprise is an imperative – urgency, scale, impact, reputation
- We have a bright future with groundbreaking discoveries, pushing the boundaries of knowledge and technology innovation for many decades to come
 - Plenty of opportunities for young scientists to contribute, enhance and direct the future of our field!
- Let's be bold and ambitious
 - Inspire young people to engage in science
 - Enable another 50 years of groundbreaking discoveries!
 - Advance the world we live in in yet unimaginable ways!

Thank you!

