A View from Fermilab: Vision for HEP in the next 50 years

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EPP 2023

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Outline

- Introduction
- Outstanding questions in Particle Physics and associated experiments
  - Nature of the Higgs boson
  - Physics associated with neutrino mass
  - Nature of Dark Matter
  - Understanding cosmic acceleration
  - Physics beyond the Standard Model
- Enabling R&D
- Particle Physics and sustainability
- Our Community and societal impact
- Summary

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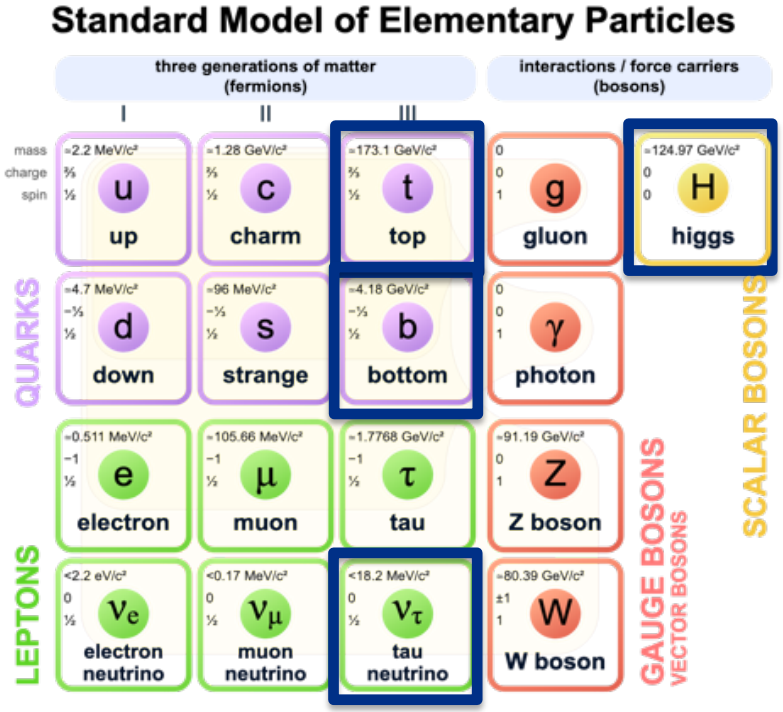
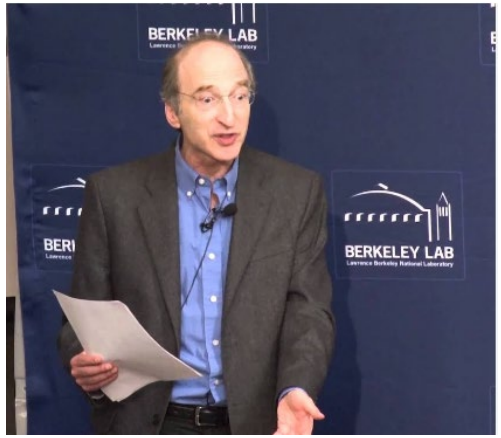
The Triumph of the Standard Model

- 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





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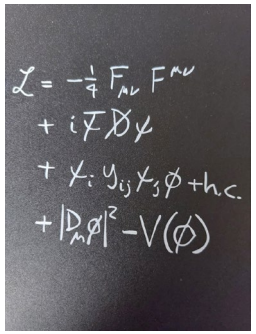
The Standard Model is incomplete



- 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
  - W mass ….

- Perhaps, the Standard Model is only a part of a bigger picture that includes new physics…

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Two fundamental lines of inquiry

How would the SM look in ~50 years?

What are some of the outstanding questions that show promise for discovery in the next decades?

And what are the experiments that will help us find the missing physics?

How would the world around us change as a result of particle physics research?

What are the enabling technologies from particle physics, and how would they evolve in the next few decades?

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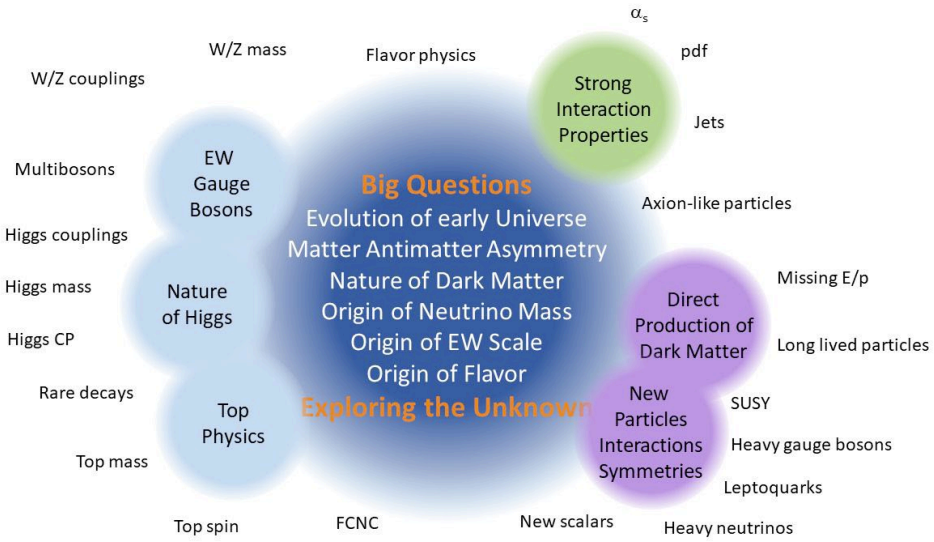
Profound Particle Physics questions with great discovery potential

- Nature of the Higgs boson
  - How does everything acquire mass?
- Physics associated with the neutrino mass
  - Matter-antimatter asymmetry
- 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



- The 2014 P5 science drivers are still compelling today
  - Ready to explore any new drivers of the current P5

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Significant advances in technology and enabling R&D

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

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This is a defining moment for the field and for Fermilab

- With the successful completion of LBNF/DUNE/PIP-II, Fermilab will become host to the first internationally conceived, constructed and operated mega-science experiment on U.S. soil
  - US/Fermilab is universally acknowledged as the world leader in neutrino science

- As it enters its next 50 years, Fermilab remains America's premier Particle Physics and Accelerator Laboratory, delivering groundbreaking science and technology innovation, underpinned by
  - a diverse and world-class and workforce
  - transformed business systems and operations
  - a renewed and sustainable campus
  - enabling regional, national and international partnerships

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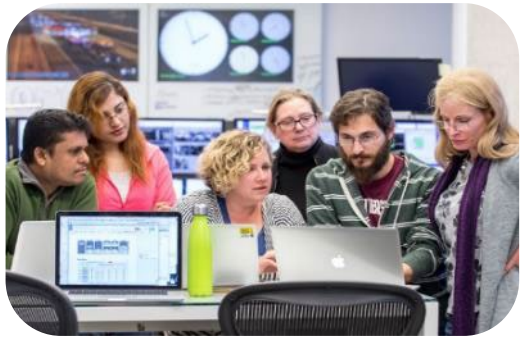
Strategic Pillars of our vision for Fermilab

Deliver groundbreaking science and technology innovation

Building for Discovery: Project Execution



Diversify and empower our workforce

Transform business operations, infrastructure management and campus sustainability

Forge strong alliances with regional, national & international institutions

Position Fermilab for a vibrant and successful future

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Science Drivers

Nature of the Higgs boson
Physics associated with neutrino mass
Nature of Dark Matter
Understanding cosmic acceleration
Physics beyond the Standard Model

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Understanding the Nature of the Higgs boson

Outstanding Questions

- Profound questions associated with the Higgs boson:
  - Is there one Higgs or many? Is it a fundamental particle or composed of others? How does it interact with neutrinos or with dark matter?
- The Higgs boson offers a unique portal into the laws of Nature, connects several areas of particle physics

Vision

- Through ATLAS and CMS, US continues to be fully engaged in the study of the Higgs with our partner CERN
  - CERN is our European sister laboratory and our strong partner in many areas
  - Fermilab continues to be the leading U.S. center for CMS and second leading center in the world after CERN

Execution

- Important measurements of the Higgs properties are currently being performed by the LHC
- Will continue at 10x luminosity of the HL-LHC

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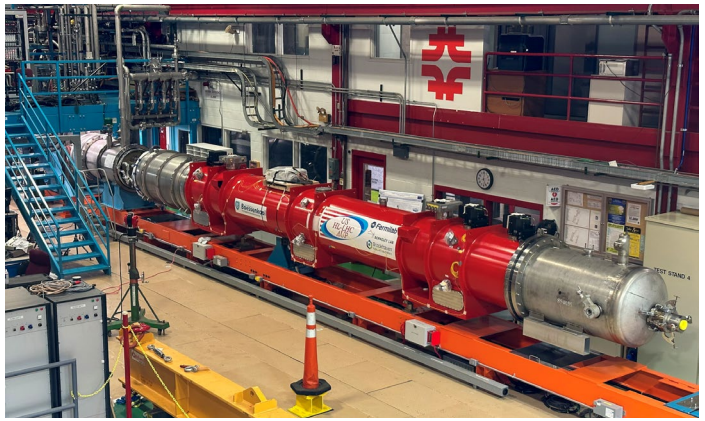
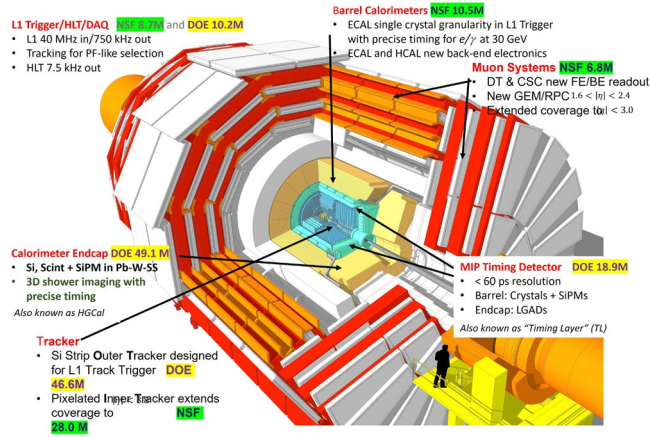
Understanding the Nature of the Higgs boson: Current status

- Maximize science from LHC Runs 2 and 3 data – *ROC is back in operations!*
- Execute HL-LHC AUP Upgrade Project
- Execute HL-LHC ATLAS and CMS Detector Upgrade Projects

Remote Operations Center (ROC) at Fermilab
CMS online shifts



HL-LHC AUP 1st CryoAssembly at Fermilab



HL-LHC CMS scope

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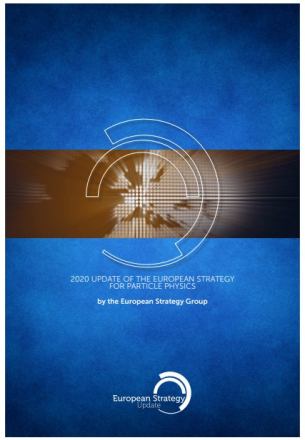
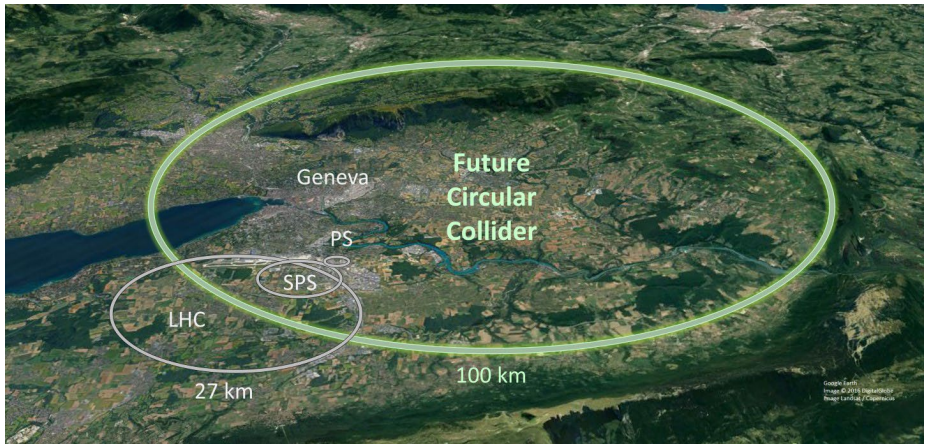
Understanding the Nature of the Higgs boson: Advancing the mission

- To unleash the full discovery potential of the Higgs through ~<1% level precision studies of its properties
  - An e+e- collider as a “Higgs factory” is needed
    - Consensus of the global HEP community and the central theme of the 2020 European strategy
    - A targeted program for accelerator & detector R&D for Higgs factory is needed
- Next generation multi-TeV energy frontier colliders probe beyond precision Higgs and can achieve greater discovery potential
  - In coordination with international partners, lay the groundwork for multi-TeV colliders by advancing accelerator and detector R&D programs

European Strategy for Particle Physics





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Physics associated with neutrino mass

Outstanding Questions

- Profound questions associated with neutrino physics remain unresolved:
  - What is the origin of the neutrino mass? How are the masses ordered? Do neutrinos and antineutrinos oscillate differently? Are there additional neutrino types?
- Neutrinos as a portal to new physics

Vision

- US, with Fermilab as the host, is universally acknowledged as the world leader in neutrino science for decades to come

Execution

- Following a series of 2014 P5 recommendations, the US has been executing a *world-leading and coherent* short and long-baseline neutrino program, hosted at Fermilab.
- Cosmic surveys, e.g. CMB-S4 and other experiments also make important contributions.

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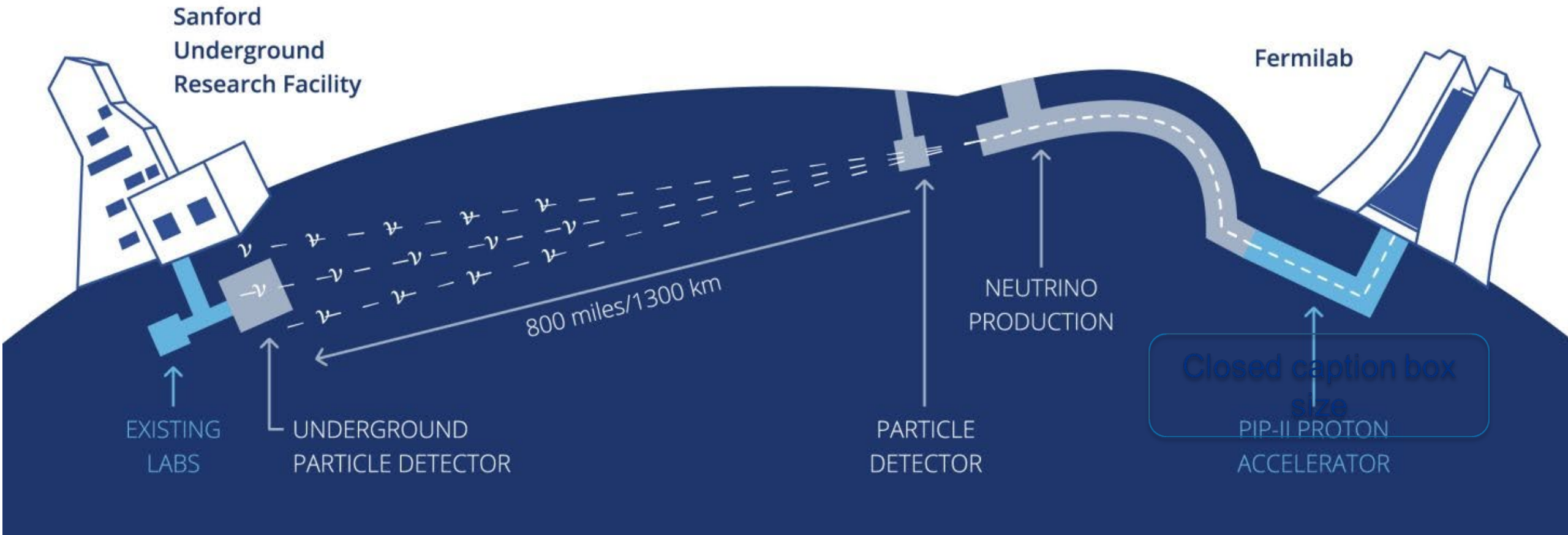
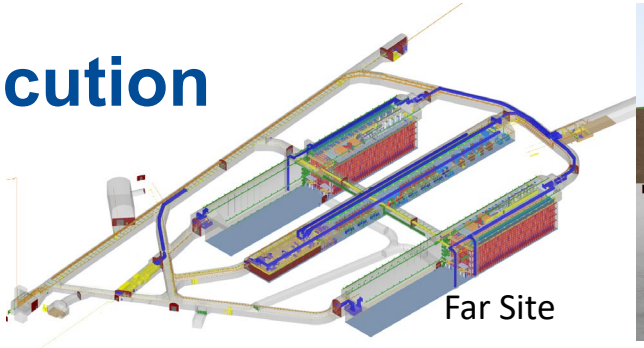
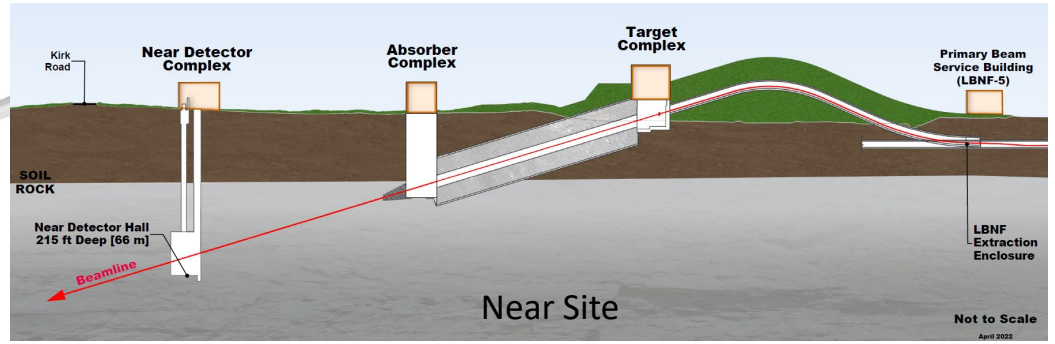
DUNE: “Best in Class” neutrino experiment, driven by LBNF and PIP-II

Delivering on LBNF/DUNE is Fermilab’s highest priority



LBNF/DUNE Phased Execution





	Component	DOE Project Scope (meets 2014 P5 minimum to proceed – Phase I)	Phase II Requirements (meets 2014 P5 goal)
Near Site	Conventional Facilities	• **Constructed to support 2.4MW** primary and neutrino beamline • **Constructed to support underground Ph I & II Near Detector**	• None
	Neutrino Beamline	• Wide-band output neutrino beam, **1.2MW** initially, designed to be **upgradeable** to 2.4MW	• 2.4MW capable target and new horns • New decay pipe window • Some additional cooling and instrumentation
	Near Detector	• US contribution to the DUNE Near Detector (Ph I)	• US contribution to more capable Near Detector (Ph II)
Far Site	Conventional Facilities	• **Surface and underground facilities & infrastructure for 4 detector modules**	• None
	Cryostats	• **For 2 detector modules** (CERN)	• For 2 detector modules
	Cryogenics	• **3 x nitrogen units**; 35 kton liquid argon for detector modules	• 1 x nitrogen unit; 35 kton liquid argon for detector modules
	Far Detector	• US contributions to 2 x DUNE LAr TPC modules	• US contributions to 2 x DUNE LAr TPC modules

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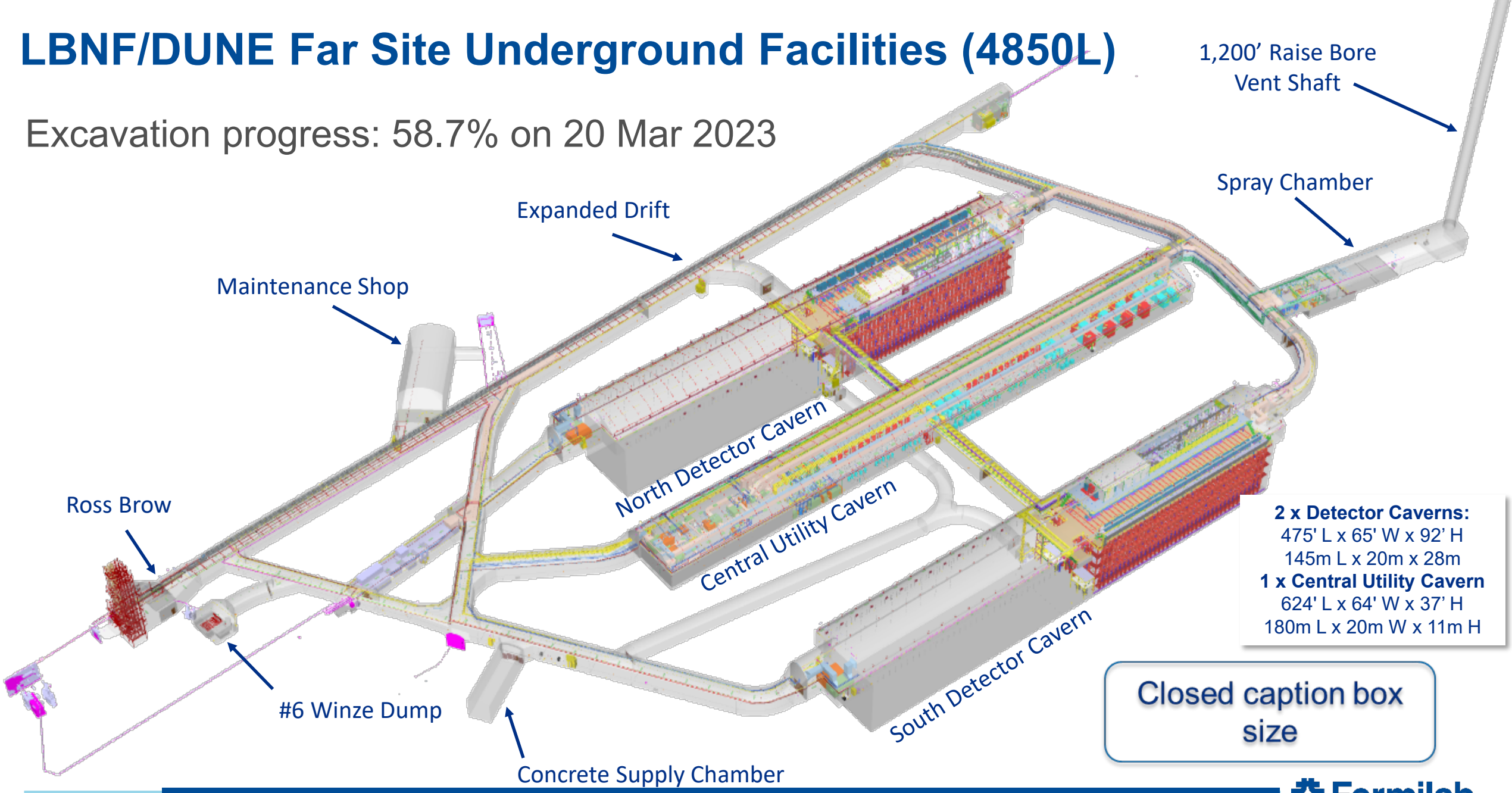
Project scope is unchanged since inception of LBNF and DUNE in 2015
Facility scope supports Phase II

LBNF/DUNE Far Site Underground Facilities (4850L)

Excavation progress: 58.7% on 20 Mar 2023



2 x Detector Caverns:
475' L x 65' W x 92’ H
145m L x 20m x 28m
1 x Central Utility Cavern
624' L x 64' W x 37’ H
180m L x 20m W x 11m H

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LBNF is constructed to accommodate full scope of DUNE

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Proton Improvement Plan – II (PIP-II)

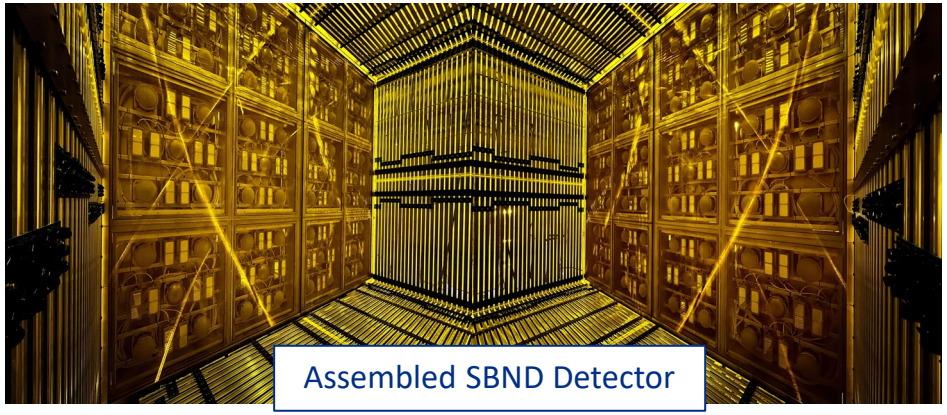
PIP-II is an essential upgrade to Fermilab accelerator complex to enable powerful, wideband neutrino beam to LBNF/DUNE, and a broad physics research program for decades to come

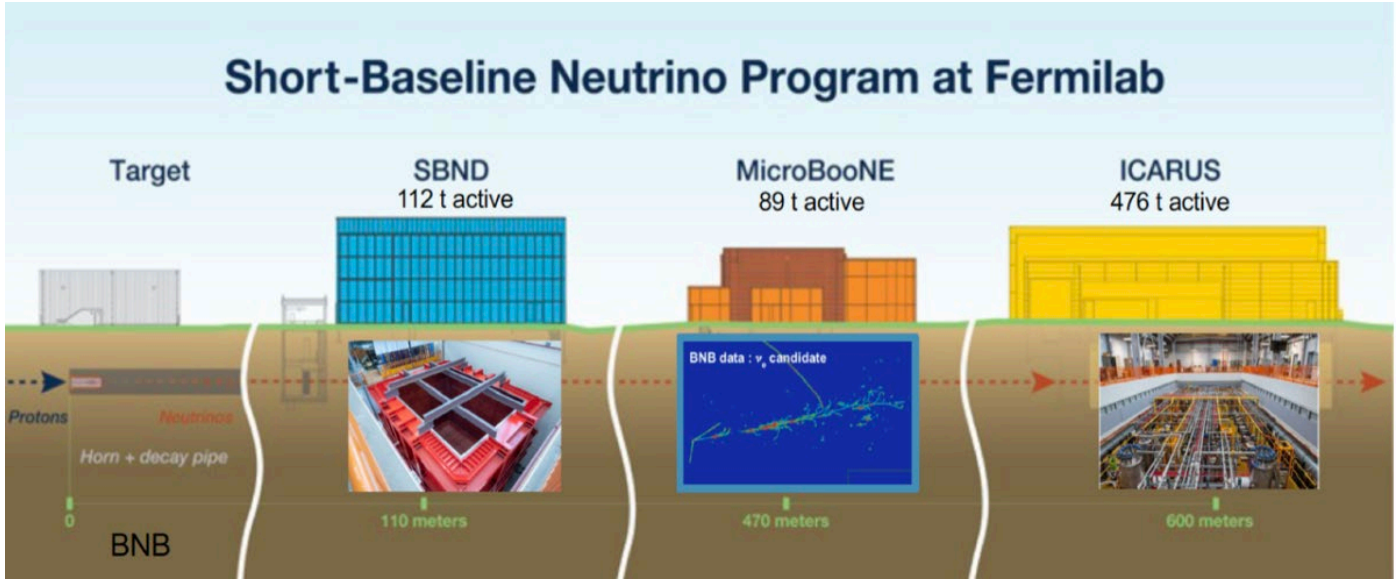
Short Baseline Neutrino (SBN) program

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

The SBN program is a 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


Assembled SBND Detector



MicroBooNE made a big splash with its flagship results:

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

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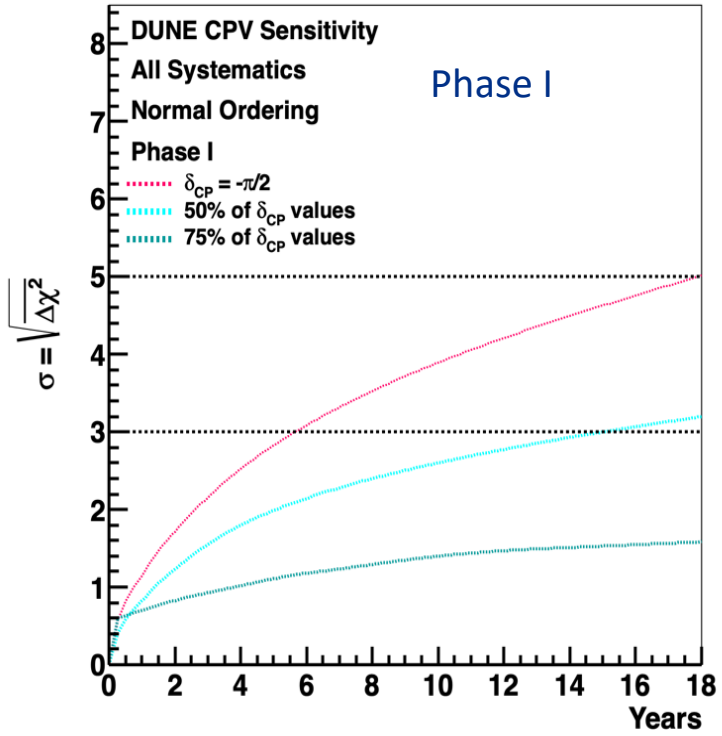
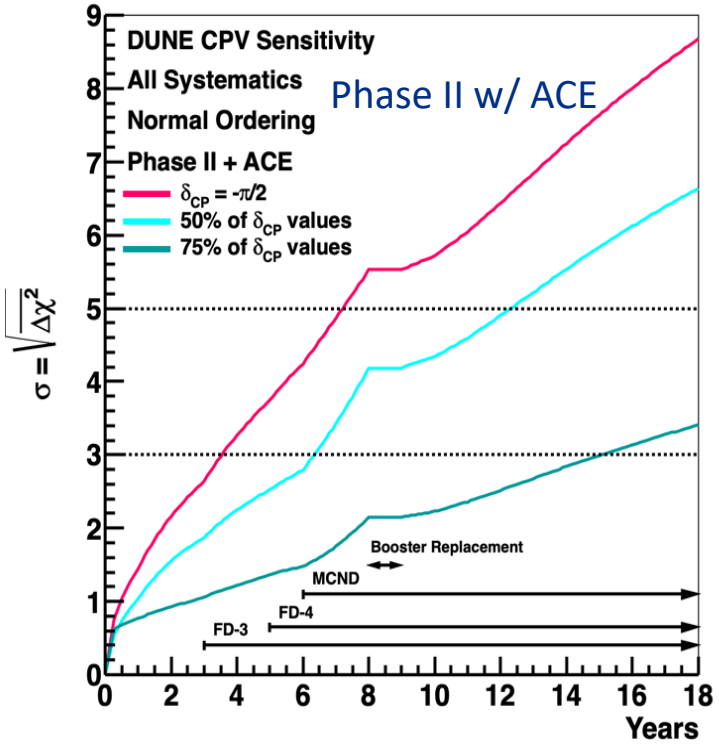
Particle Physics is now more global than ever: National and International Engagements

- 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
- Fermilab has blazed a new trail in international partnerships for the DOE/SC

Physics associated with Neutrino Mass: Advancing the mission

- To complete the 2014 P5 vision and achieve world-first measurements from DUNE, we need:
  - two additional Far Detectors
  - a more capable Near Detector
  - reliable, higher intensity beam





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The Fermilab Accelerator Complex Evolution (ACE)

ACE has two components

- **Upgrades to the Main Injector and target station** will allow DUNE to achieve world-leading results on an accelerated schedule
- **A Booster replacement** will
  - Provide a robust and **reliable** platform for the future of the Fermilab accelerator complex
  - Ensure high intensity for DUNE Phase II → CP Violation *measurement*
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 2-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

Capability
Capacity
Reliability

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ACE pushes the state-of-the-art in accelerator technology and will be executed with national and international partners cost-effectively

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Nature of Dark Matter

- Outstanding Questions
  - Astrophysical observations imply that the known particles make up only ~ 1/6 of the total matter in the universe. The rest is Dark Matter. Properties of DM particles are largely unknown.
- Vision
  - The US is a world-leader in the search for dark matter.
  - Fermilab is both a leader and an essential partner bringing its core capabilities to bear in this search.
  - With ACE, Fermilab is enabling excellent opportunities for accelerator-based dark sector searches at modest cost and scale
- Execution:
  - The challenge of discovery and characterization of DM interactions with ordinary matter requires a broad campaign of laboratory searches and cosmic surveys, as well as complementary experimental techniques and international cooperation.
    - Direct detection experiments: G2 → G3
    - Indirect detection, cosmic surveys: DESI, LSST, SPEC-S5
    - Experiments at the LHC and future colliders
    - Fixed target accelerator experiments

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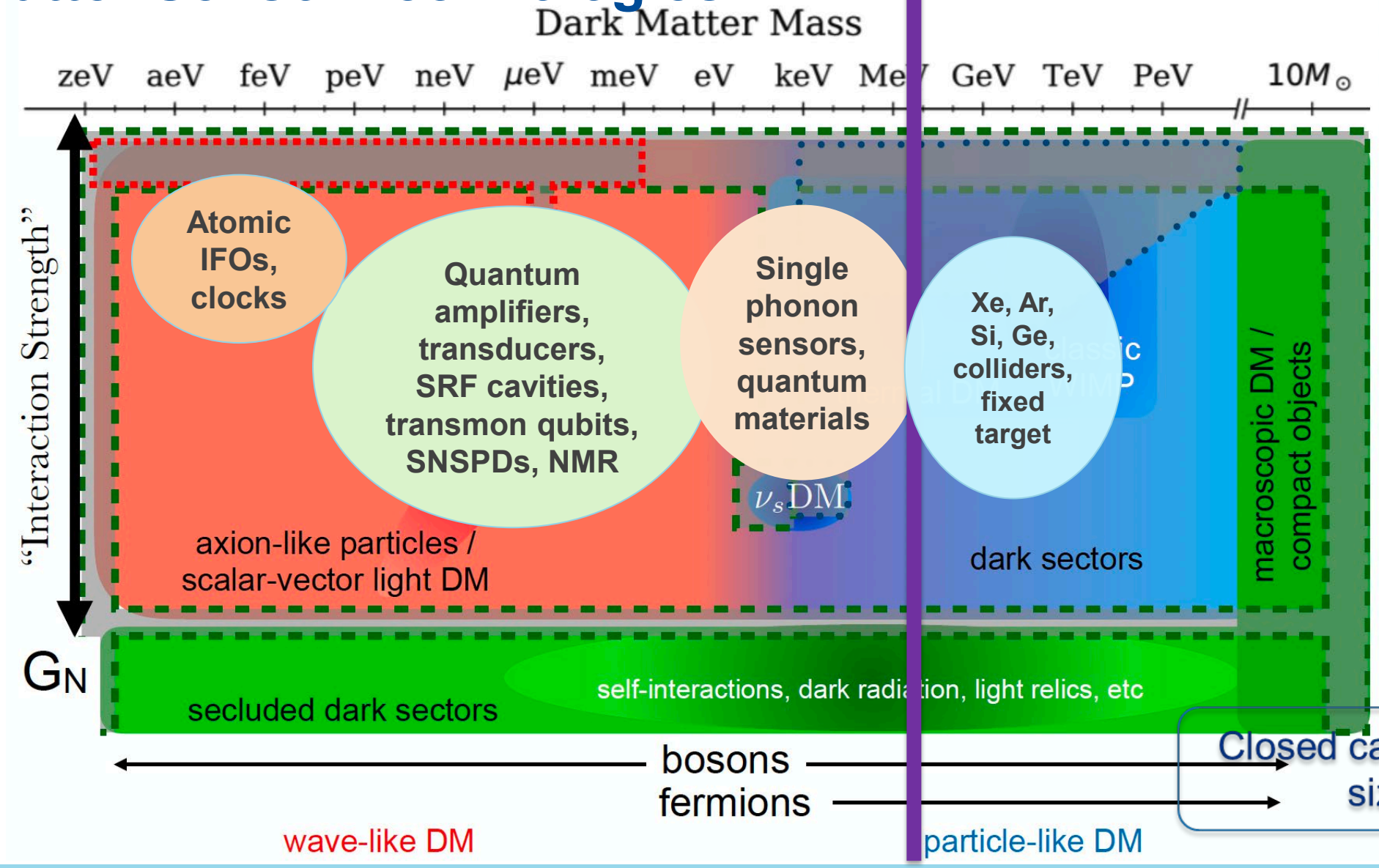
Dark Matter Sensor Technologies



Cartoon from Snowmass

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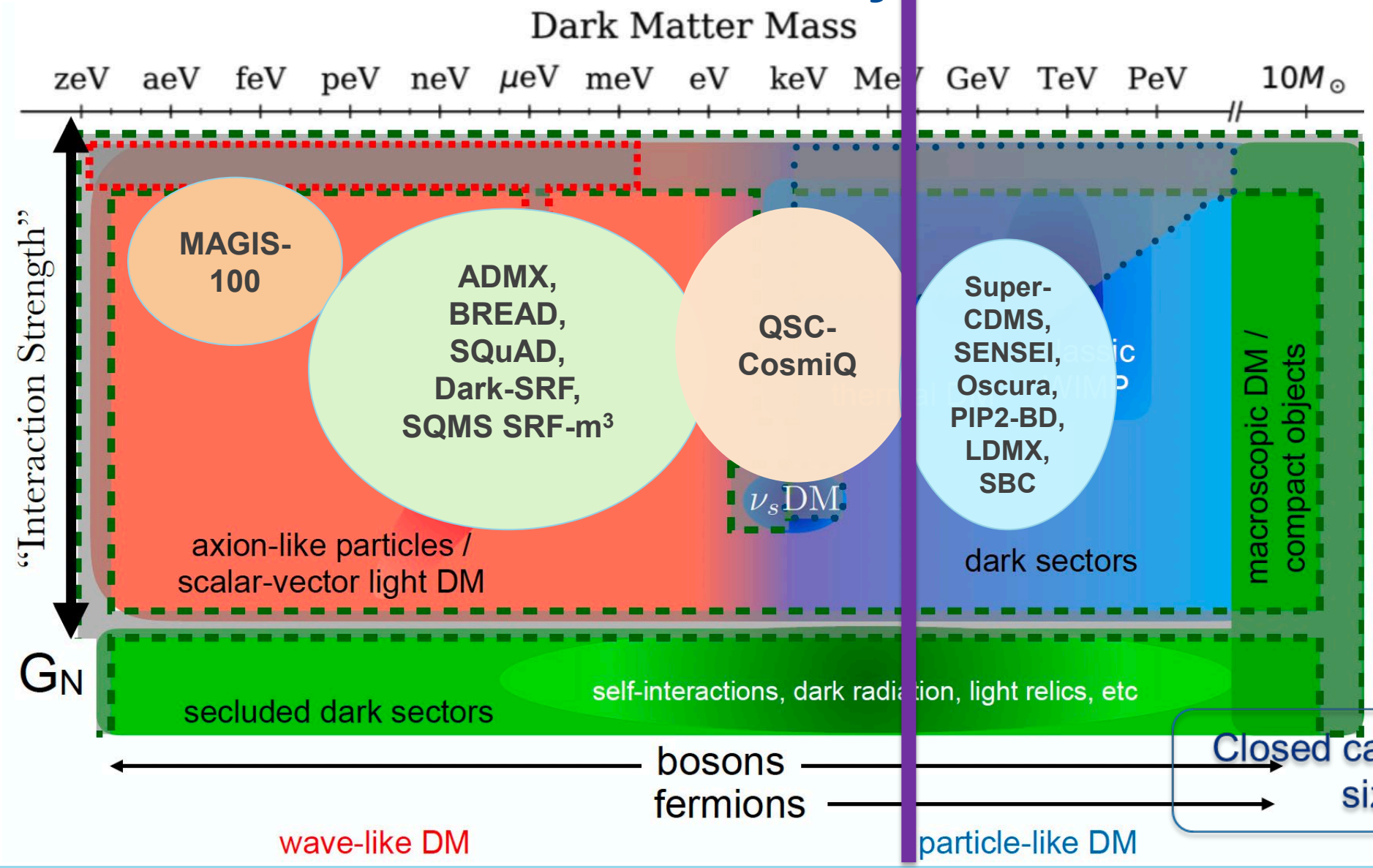
US Dark Matter Initiatives – A vast array



Cartoon from Snowmass

Many more experiments not listed

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Understanding cosmic acceleration

- Outstanding Questions
  - In our quest to piece together the story of the origin and evolution of the universe, we need to understand the two periods of accelerated expansion of the Universe. We know very little about the fundamental physics of dark energy and inflation. Next generation of cosmological probes have the potential for important insights into the physics that drove these phenomena.

- Vision
  - Fermilab is an essential partner in world-leading cosmic science experiments, contributing innovative R&D and unique capabilities toward future experiments, notably CMB-S4.

- Execution
  - Transition from DES → DESI, Rubin LSST/DESC, SPEC-S5
  - CMB-S4 is the highest priority future cosmic frontier effort
  - Combine early-epoch data from CMB with late-epoch data from LSST

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Physics beyond the Standard Model

- Outstanding Questions
  - There is clear evidence of new phenomena beyond the Standard Model
  - No mass/energy scale for BSM physics
- Vision:
  - Fermilab is a world leader in accelerator-based Charged-Lepton Flavor Violation (CLFV) experiments driven by intense particle beams enabled by PIP-II and ACE.
  - With our partner CERN, US continues to be fully engaged in search for BSM physics, through neutrinos and colliders.
  - Fermilab hosts a next generation multi-TeV energy frontier collider, as a global endeavor, following the completion of DUNE.
- Execution
  - Detect quantum influence of new particles in lower energy phenomena/rare processes: Mu2e, Muon g-2; Belle-II and LHCb; Proton decay at DUNE
  - Search for new particles at the LHC and HL-LHC
  - Evolve accelerator complex to a world-leading facility to probe the highest energy and provide the bandwidth for new discoveries
    - ACE → Large scale multi-TeV energy frontier collider

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Muon Program at Fermilab: Current status

- Muon g-2: Achieved statistics goal of 21x BNL data set!
  - Final result expected in 2025
  - Updates from the Muon g-2 Theory Initiative expected on the same timescale
- Mu2e: Project under construction, start science in 2026
- Future developments: Mu2e-II, other upgrades in 2030s

1st half of Transport Solenoid cryostated

Production Solenoid Cold Mass Assembly

1st Calorimeter disk instrumented

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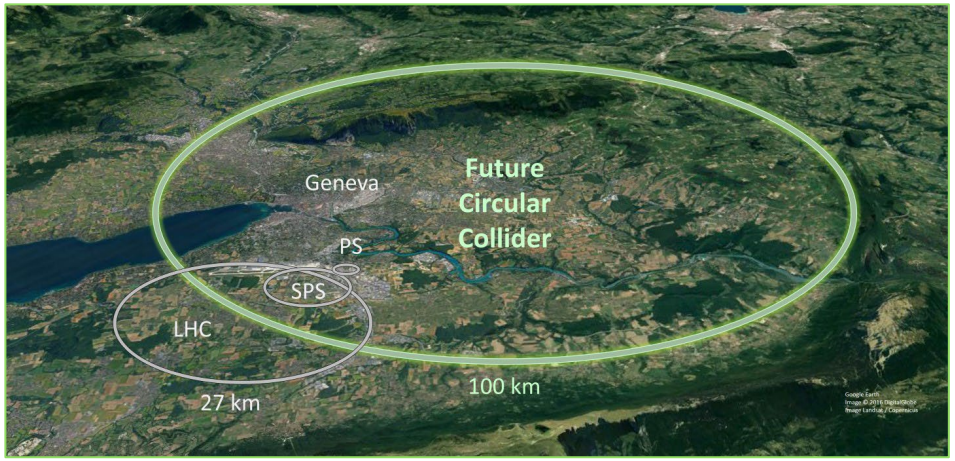
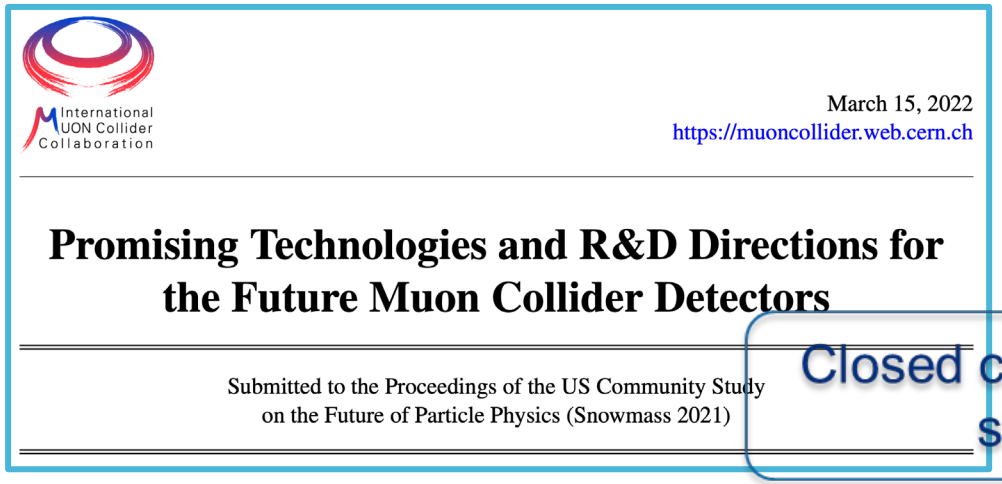
Next generation multi-TeV energy frontier colliders

- Beyond the Higgs Factory, a next generation multi-TeV energy frontier collider could extend the reach for new physics in any scenario. Such an endeavor would require global coordination and collaboration and the US is poised to play a major role:
  - Leveraging PIP-II and ACE, the US is well positioned to host a world-leading energy frontier collider as the next major facility at Fermilab, conceived and executed as a global endeavor.
  - Pursue globally coordinated accelerator & detector R&D towards a next generation energy frontier collider
- In order to maintain its leadership position in the world and ensure a healthy and vibrant accelerator workforce, the US must host world-class facilities that engage the global scientific community.




International
MUON Collider
Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

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Enabling R&D

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

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Accelerator Science & Technology

- Changing the Cost-Capability Curve of Accelerators
  - Vigorous, targeted and globally coordinated R&D is required to make future colliders feasible at a reasonable cost. The US is a world-leader in critical technologies for colliders.

- Accelerator R&D on challenging technologies in the US ensures our continued competitiveness by:
  - building and retaining the strong and diverse workforce of accelerator physicists to realize the HEP long-term plans
  - enabling development of critical technologies.

- Strengthening and expanding our beam test facilities and capabilities will ensure our competitiveness with respect to worldwide capabilities.

- In the pursuit of Accelerator Science in its own right.

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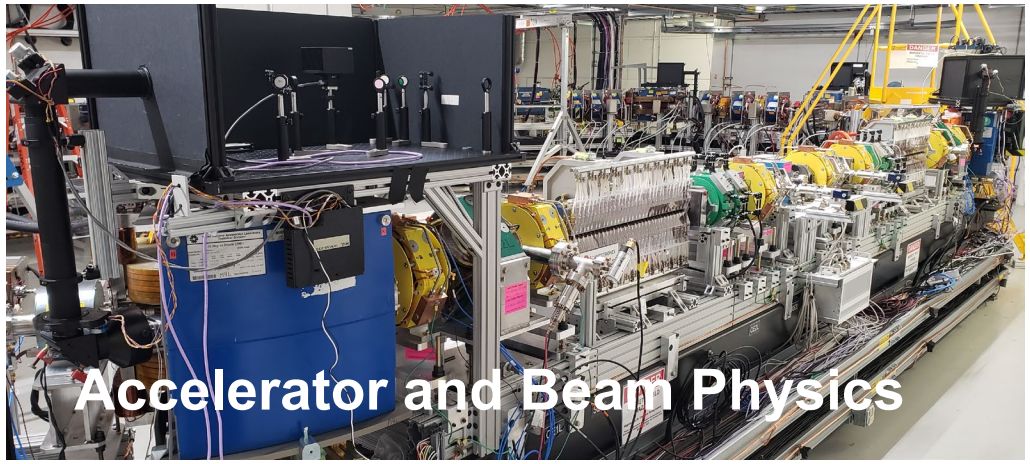
Accelerator Science & Technology

Vision: Fermilab is a world-leader in Accelerator Science & Technology 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.



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Fermilab is addressing the needs of many DOE/SC program offices

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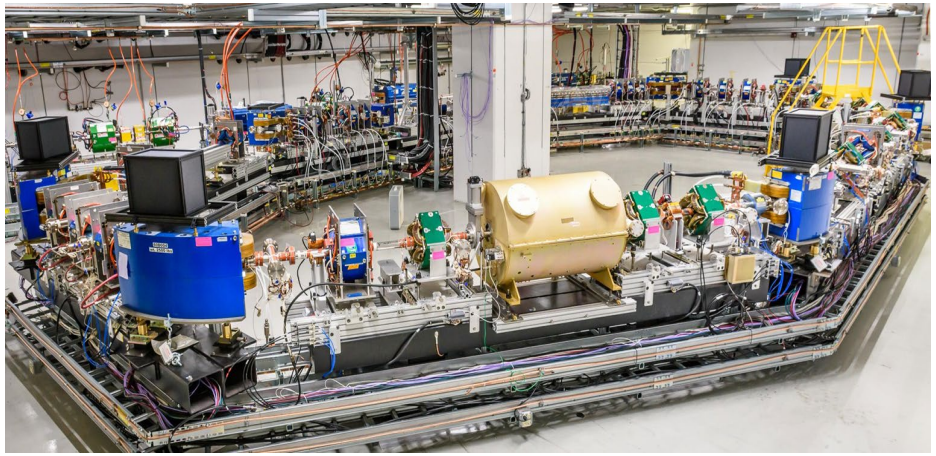
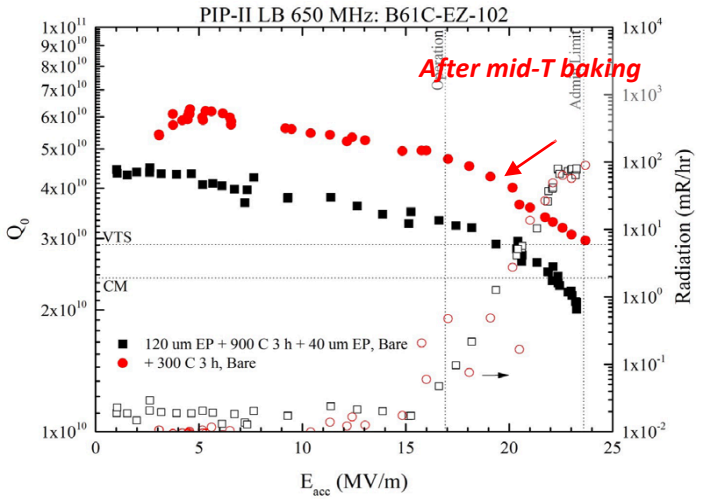
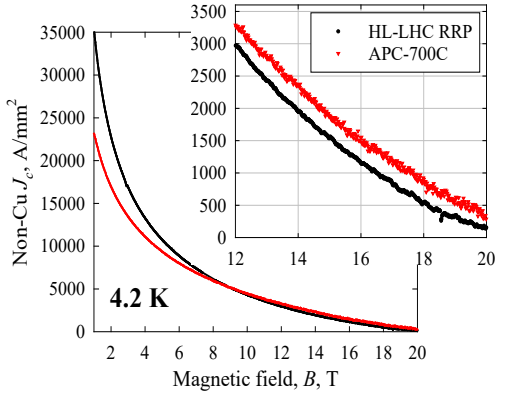
Accelerator Science & Technology: Notable achievements



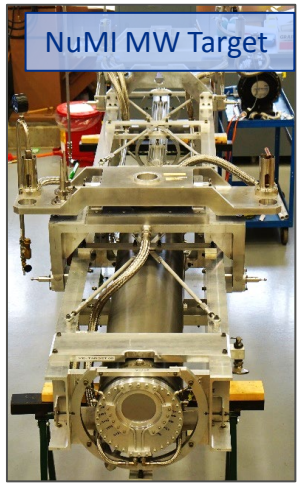
First experimental demonstration of 6D Optical Stochastic Cooling published in *Nature* in 2022



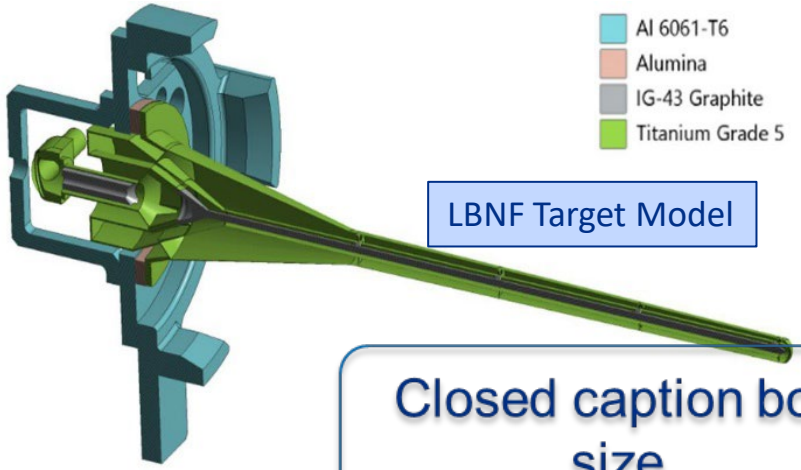


Nb_3Sn wire R&D can help realize future hadron collider and muon collider

NuMI MW Horn



NuMI MW Target



LBNF Target Model

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Fermilab accelerator technology enables SC Mission: LCLS-II, LCLS-II-HE, PPU

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Accelerator Science & Technology:
Realize a step function in cost capability curve of future accelerators

Accelerator and Beam Physics

- Deliver and exploit the world's highest power beams for LBNF/DUNE and a broad discovery program
  - Design and build ACE
- Advance designs of next generation multi-TeV colliders
- Develop and exploit FAST/IOTA beam test facility

Superconducting RF

- Explore limits to SRF performance for future accelerators
- Develop innovative treatments for Nb; investigate new materials, geometries, e.g. Nb_3Sn, thin-film (including high-T_c) superconductors

High-Power Targetry

- Significantly ramp-up multi-pronged HPT R&D, expertise and capabilities to successfully and reliably deliver the full 2.4 MW LBNF/DUNE mission, and other programs.
- Play a major role in developing future materials & technologies

High Field Magnets

- Enable the USMDP and extensions
- Design, fabricate and test high-T superconducting quadrupole magnet
- Develop and demonstrate Nb_3Sn wires for 16-18T-class magnets

Advanced Accelerator Concepts

- Develop near-term applications as essential to progress towards HEP colliders and ensure international competitiveness
- Research on advanced accelerator R&D towards future high energy colliders

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In all these areas, engage in vigorous R&D towards next generation colliders in collaboration and coordination with national and international partners

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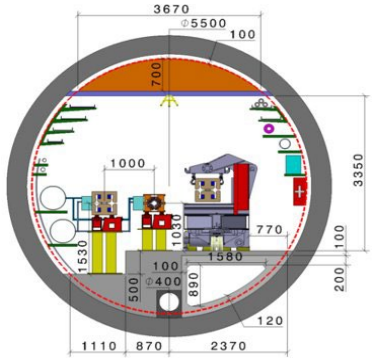
US Magnet Development Program

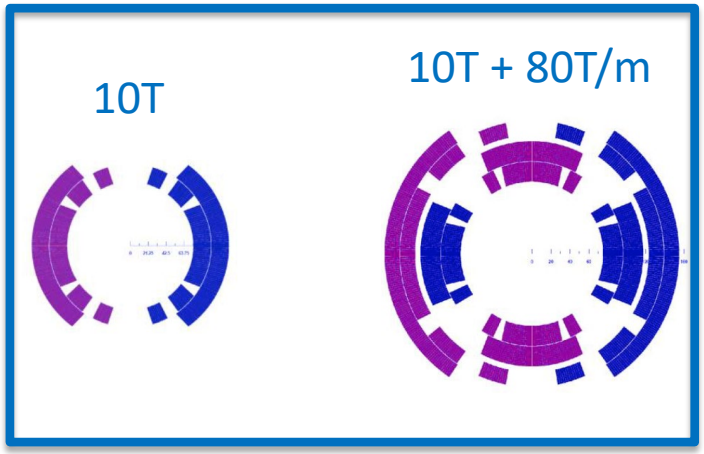
BERKELEY LAB · Brookhaven National Laboratory · Fermilab · NATIONAL HIGH MAGNETIC FIELD LABORATORY · U.S. MAGNET DEVELOPMENT PROGRAM

Collaboration bringing together expertise and resources for the development of superconducting materials and magnets. Focuses on fundamental accelerator magnet R&D, providing key magnet technologies that benefit all future accelerators. Scope needs to be enhanced for future colliders

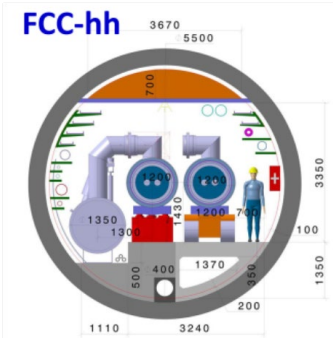
Magnet R&D for future multi-TeV Colliders



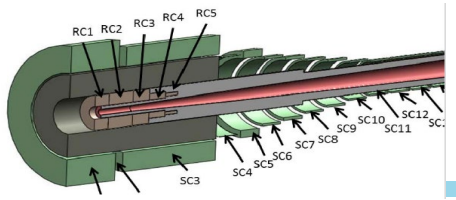
Low field, HTS operated at LN_2 temp to significantly reduce power consumption



High field and fast ramping dipoles
– large bore, high radiation load at the mid-plane



High field dipoles (up to 24 T) – Nb_3Sn or HTS (Power consumption may demand HTS operating at higher temperature)



Very high field solenoids
– 32T already demonstrated

USMDP Goals

GOAL 1: Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.
GOAL 2: Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.
GOAL 3: Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.
GOAL 4: Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

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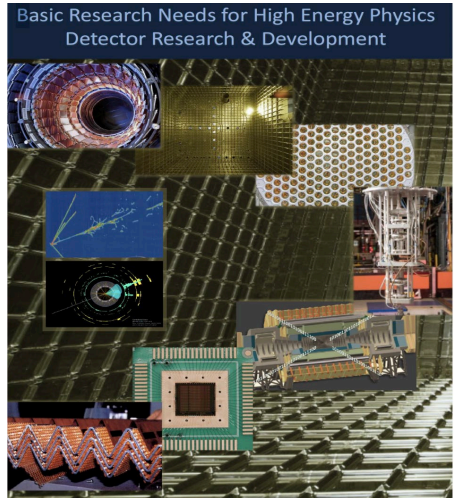
Detector R&D: New detector technologies are transformative

A strong program in detector research is necessary to enable planned experiments and explore new directions

- **Fermilab enables targeted R&D including**
  - DUNE, Future Collider Detectors – coordinating with international partners, transformative new technologies for Dark Matter Searches

- **Fermilab enables blue-sky R&D**
  - Addressing four grand challenges of the DOE Detector and Instrumentation Basic Research Needs
    - Advancing HEP detectors to new regimes of sensitivity
    - Using Integration to enable scalability for HEP sensors
    - Building next-generation HEP detectors with novel materials & advanced techniques
    - Mastering extreme environments and data rates in HEP experiments



New technologies in…

- Quantum
- Solid State
- Calorimetry
- Readout and ASICs
- Photodetectors
- Noble Liquids
- TDAQ

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Computing: A long-term view

Computing is the bridge between experimental data and discovery

Fermilab will enable HEP science by:

- Providing **storage of and access to the world's largest scientific data sets**
  - Fermilab continues to lead in data storage and processing by leveraging and augmenting commercial technologies
  - Vision: dynamically configurable data facility supporting the use of curated datasets and analysis on streamed data, leveraging DOE/SC resources
- Leading the community in the **adoption of new computational technologies**
  - Such as hybrid classical (CPU, GPU, TPU) and quantum computing (QC) resources
- Exploiting and enabling **artificial intelligence** approaches to all aspects of computing and HEP science
- Embracing the broader scientific computing community
  - We **bring applied math and computer science to HEP** and bring **HEP to applied math and computer science**

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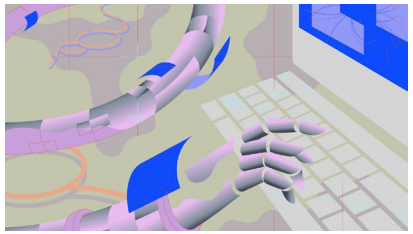
AI at Fermilab: A long-term view



AI is a **pervasive force multiplier** across the entire scientific continuum enabling transformative capabilities to **accelerate HEP Science**

- **Accelerators**: Highest power beams ever with near-perfect up-time, predictive maintenance and minimal human intervention to enable new accelerator-driven discoveries
- **Experiments**: Accelerated discoveries with AI-enabled **automation** and **optimization**
  - **Experiment design** – detector technologies, configuration, run planning
  - **Readout and control** – optimal distributed sensing, data reduction, and real-time adaptive learning
  - **Data processing and simulation** – generative modeling and optimal feature extraction
  - **Automated data mining, analysis, and interpretation –** hypothesis generation and data-driven discovery
- **Unique HEP challenges** that surpass other scientific domains and industry **will spur innovation in AI techniques and technology** that will advance discoveries in other sciences, society, industry

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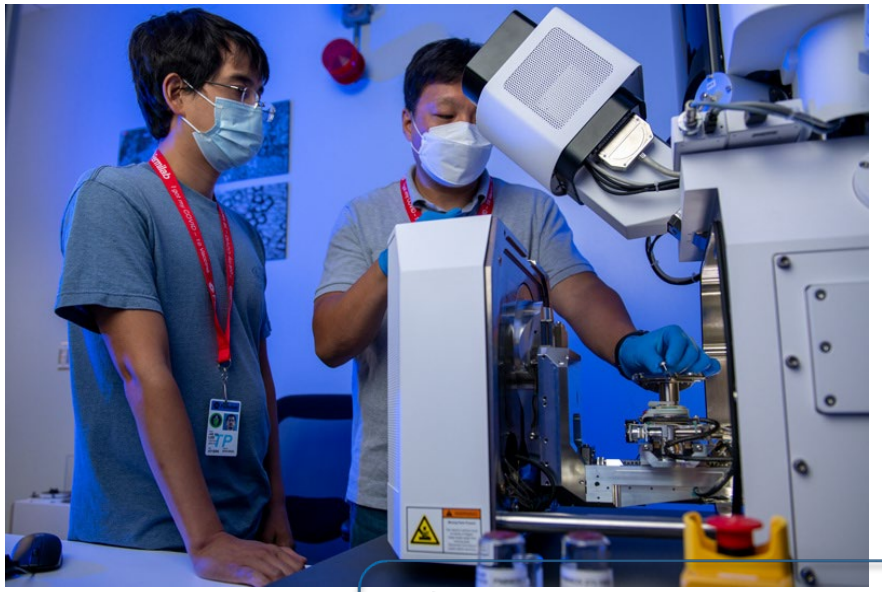
Quantum Information Science & Technology

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.



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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

Led by FNAL, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

24 Institutions
> 400 Researchers
> 100 students/postdocs

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NIST
INFN
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Stanford University
UNIVERSITY OF ILLINOIS
URBANA-CHAMPAIGN
RUTGERS
IN SUPREMÆ DIGNITATIS
1343
UNIVERSITÀ DI PISA
University of Colorado Boulder
ILLINOIS INSTITUTE OF TECHNOLOGY
JOHNS HOPKINS UNIVERSITY
Temple University
COLORADO SCHOOL OF MINES
THE UNIVERSITY OF ARIZONA
Unitary Fund
UNIVERSITY OF MINNESOTA
NYU
Goldman Sachs
LSU
LOCKHEED MARTIN
JANIS

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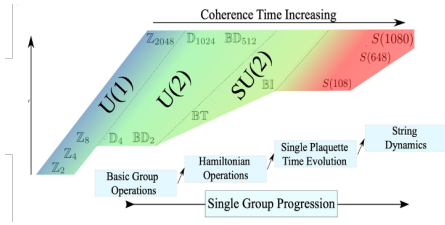
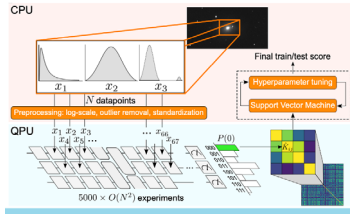
QIS&T at Fermilab: A long-term view

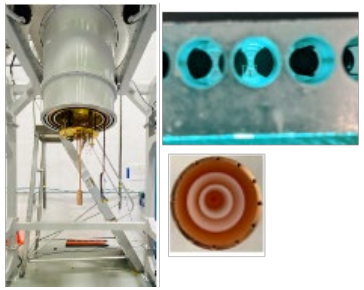
QIS for HEP and HEP for QIS



Leveraging HEP core capabilities, Fermilab is pursuing a multi-pronged and vibrant QIS&T program (lead SQMS, strong participation at QSC, broad research program) aiming to enable HEP science and advance QIS&T. Our long-term vision for its impact includes:



- Distributed **quantum sensors** for large scale experiments for breakthrough discovery
  - Examples: dark matter covering most of available parameter space, gravitational waves, cosmic neutrinos.
- **Quantum systems** enabling foundational science experiments
  - QC and quantum networks to provide insight in the emergence of time, connection of gravity to quantum entanglement
- **Quantum simulation** of quantum field theory
  - QC the only systems that allow quantum simulation of QFT E.g., QCD problems were perturbative and LQCD aren't enough e.g. fragmentation, hadronization
- **Quantum computing** enabling advanced data science capabilities for discovery
  - Analysis of quantum data with QCs running quantum algorithms (e.g., QML) will allow us to fully realize the potential of applications above



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Microelectronics: A long-term view

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 while at the same time achieve societal impact by creating disruptive technologies

- Enable breakthrough discovery by developing **integrated precision sensing with computing and communication technologies**
  - Future particle detectors for precision science will generate unprecedented amount of data, overcome the data challenge by developing microelectronics that enable real-time data processing
- Impactful **hardware development for Quantum, AI at the edge, 6G and beyond**
  - Accelerate innovation by enabling lab to fab transition of fundamental research by creating path-finder discovery platforms
- **Microelectronics workforce**
  - Foster a pipeline of innovation ideas and talent, create a regional center of excellence with partners
- Support and develop **US-based advance manufacturing** technology
  - Work with foundries and industry to setup robust and reliable integration and packaging capabilities for low volume prototyping

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How would the world around us change as a result of Particle Physics research?

Particle physics research pursues extremely difficult scientific questions. HEP scientists are early adopters and developers of emerging technologies and often the first to deploy them at larger scale. Some examples:

- HEP scientists first to execute distributed high throughput computing at a global scale; later Fermilab experts helped U.S. commercial **cloud providers Google and Amazon** develop competitive capabilities in this area.
- DOE HEP scientists were the first to develop **cryogenic microelectronics** at large scale for DUNE.
- DOE made large investments in infrastructure and expertise for **superconducting materials and devices** for SQMS Center.
- Detecting dark matter is fueling rapid advances in the development of **quantum sensors**.
- HEP particle detectors already deploy **timing systems with a thousand times better precision** than commercially available.
- U.S. HEP scientists working with U.S. industry developed, and deploying, the world's most advanced "**Artificial Intelligence (AI) on a chip**".

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US HEP is a leader in multiple emerging technologies of strategic importance to the nation and to US industrial competitiveness

Particle Physics and Sustainability

- We must devise strategies for sustainable developments with the goal of increasing the energy efficiency over the life cycle of projects: reduce, re-use, recycle
- Include energy sustainability as a KPP for new research infrastructure projects (already exists in HPC)
- Fermilab plans to develop a strategic plan for sustainability, including large scale projects.

Sustainability at Fermilab and the PIP-II Project

Tiffany Price

6th ESSRI Workshop

29 September 2022

Sustainability within PIP-II

PIP-II Workshop

- Established five goals for the project
- Brainstorming sessions to identify and explore strategies, review lessons learned, and to develop specific, executable plans to improve sustainability features for PIP-II

1. Energy management at accelerator facilities and resulting experience
2. Energy efficient technologies
3. Campus and building management
4. Energy recovery
5. Waste heat recovery

7

Environmental and societal impact

A. The energy efficiency of present and future accelerators, and of computing facilities, is and should remain an area requiring constant attention. Travel also represents an environmental challenge, due to the international nature of the field. ***The environmental impact of particle physics activities should continue to be carefully studied and minimised. A detailed plan for the minimisation of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project. Alternatives to travel should be explored and encouraged.***

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Our Community and Societal Impact

- From Snowmass:

  A cohesive, strategic approach to promoting diversity, equity and inclusion in high-energy physics, and to improving community outreach and engagement, is required.

- Workforce development: Engage and train the next generation of diverse and empowered workforce
- Ensure a culture of safety, including psychological safety
- Communication: share our excitement with the broader community, inspire the next generation
- Particle Physics developments provide important benefits to society
  - Medical applications (imaging, therapy)
  - Compact accelerators
  - Computing
  - Technology innovation

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Summary

- The questions of our field are profound, the tools are exquisite, our community is world-class, support and funding have been rising
  - We are undertaking some of the most challenging projects ever and succeeding
- 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!

Fermilab is the steward of national HEP capabilities, and we invite the community to help us define and exploit these capabilities to enable discovery

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Thank you!

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