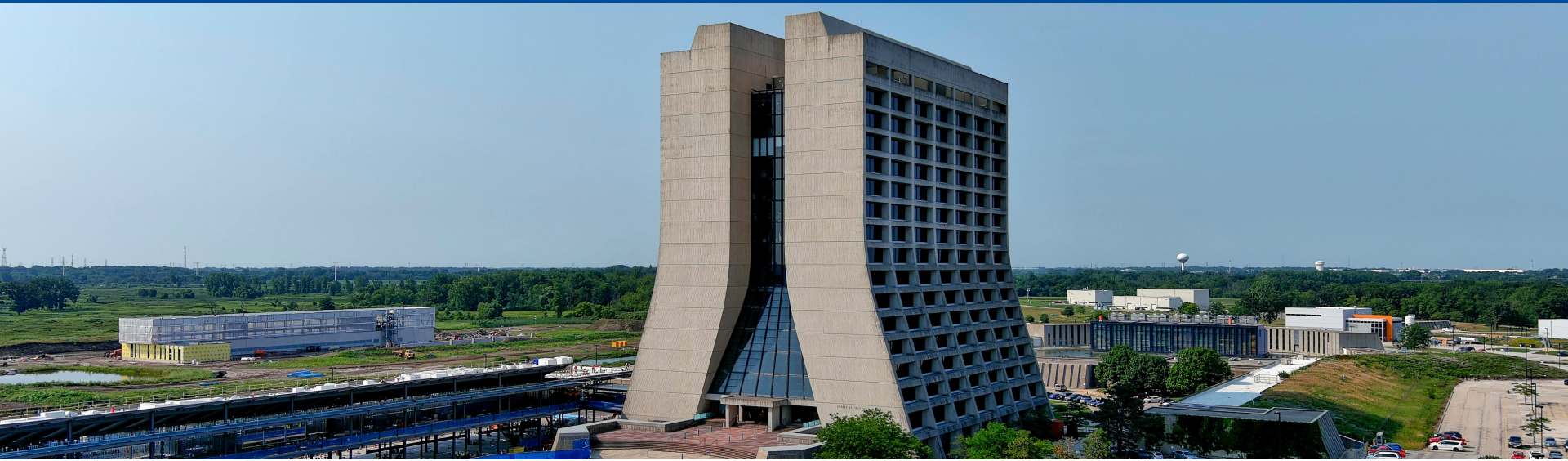

Fermilab's Science Priorities

James Amundson, *Fermilab Associate Lab Director for Computational Science and AI*

Open Meeting of the European Laboratory Directors Group

July 11, 2023

Vision for US Particle Physics

- With our international partners, realize the full scope of the **best-in-class DUNE experiment** in a timely fashion
- With our international partners, participate as strong contributors in the **LHC and HL-LHC**
- Lay the foundation for an **international Higgs factory** and a **next-generation multi-TeV collider**
- Enable the accelerator complex to **probe the unknown** with a broad, balanced, diverse, discovery program
- Uncover the mysteries of the universe with **CMB-S4 and dark sector initiatives**
- Engage in enhanced **Accelerator R&D, Detector R&D,** and **Theory** efforts to enable the science
- Excel in National Initiatives in **Microelectronics, QIS,** and **AI/ML**

Engage, train, and support a **diverse community**

Fermilab

How to accomplish our science

Exploit the science of the current program to its fullest

Execute our current project portfolio with excellence

Lay the foundation for our future program

- **Continue to be a partner of choice** in international science
- **Serve as an excellent host** for our US-based world-leading international facilities
- **Find the right balance**
  - between executing the current program, laying the foundation for the future, and having free energy to respond to new discoveries;
  - between small, medium and large-scale experiments; and
  - between projects, operations, and research
- **Build and sustain the diverse workforce** for the next generation of everything we do

Commitment to Equity, Diversity, Inclusion, and Accessibility

The principles of equity, diversity, inclusion, and accessibility (EDIA) are crucial for maintaining a just and healthy work environment as well as for maximizing the scientific output of the basic research community; they constitute a core set of values of the community. HEP is a global, open enterprise.

- Fermilab, as a focal point of the US HEP community, strives to be an exemplar for leading EDIA initiatives in HEP

- Fermilab believes that leadership in EDIA requires creating **a culture with real, actionable consequences**

Vision for the Fermilab Facility

- The Fermilab Facility must have the capability to support
  - **The full DUNE program**, including both Phase I and Phase II
  - An ongoing program of **small- and medium-scale experiments**
  - **Research into future accelerators**
- … all while maintaining enough **capacity to respond to developments** in the field

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
  - 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
  - Provide a robust and **reliable** platform for the future of the Fermilab accelerator complex
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

Capability
Capacity
Reliability

More on ACE later in this talk!

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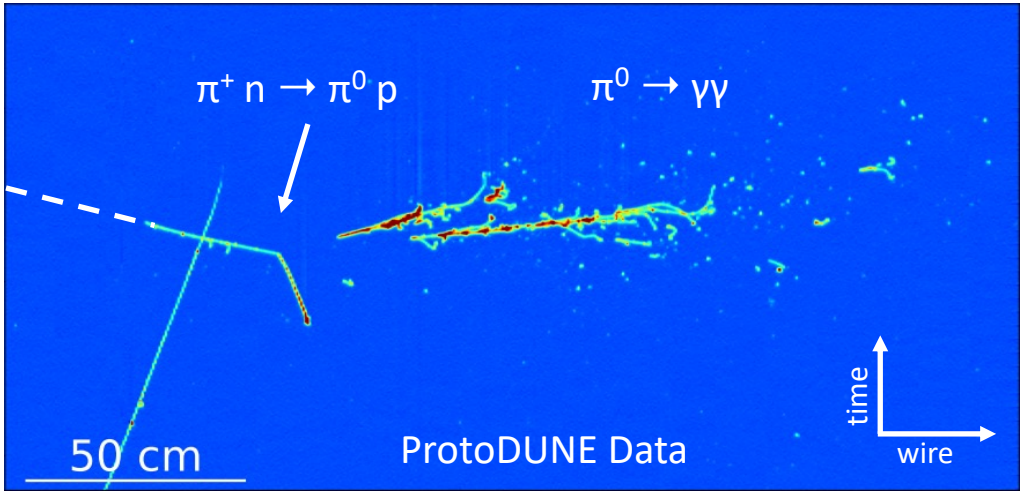
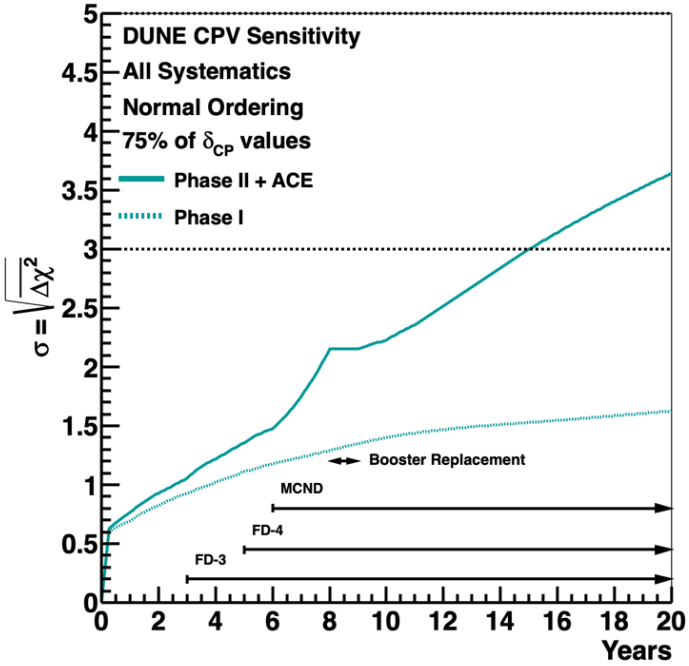
Commit to the Full DUNE Program

DUNE will be a best-in-class neutrino experiment and comprehensively test the 3-neutrino paradigm with the completion of its Phase II upgrades:

- Additional far detector mass to reduce statistical uncertainties
- More capable near detector to reduce systematic uncertainties





CP violation sensitivity to 75% of δ_{CP} values

- Meets goal established in 2014 P5 recommendations

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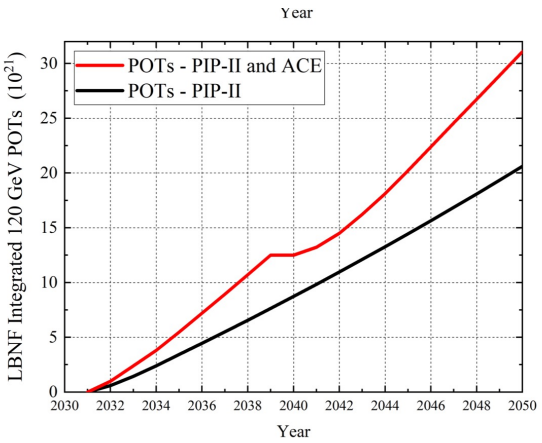
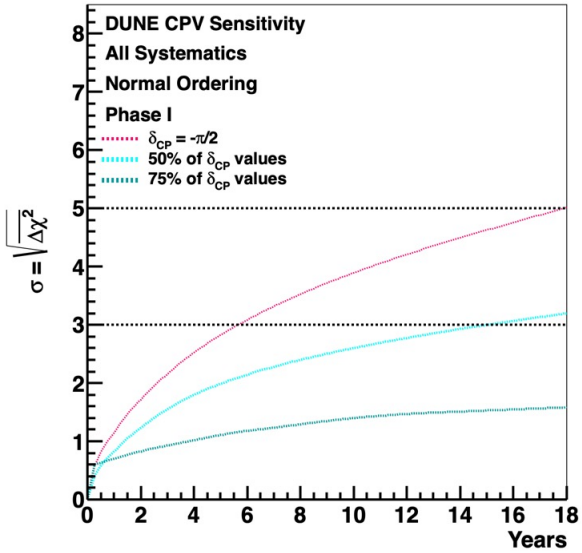
Enabling World-first Measurements from DUNE

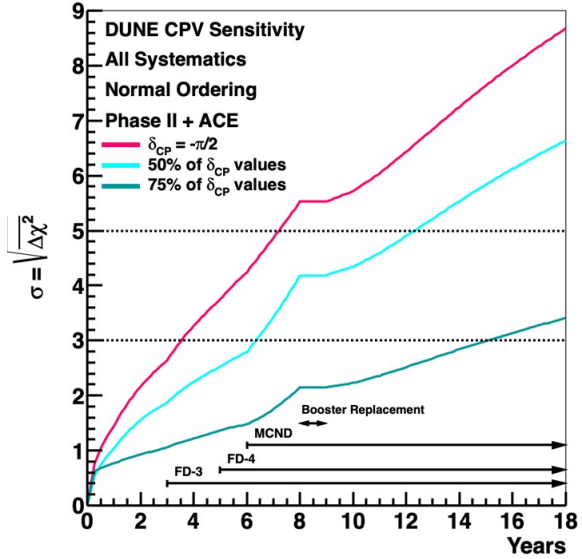
Early ACE upgrades to the Main Injector and target station, combined with completing DUNE Phase I **puts DUNE and Hyper-K on a similar timescale for discovery**



POT with ACE upgrades



Phase I



Phase II w/ ACE

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Fermilab's Short-baseline Accelerator ν Program

Suite of medium-scale neutrino experiments vital for the field

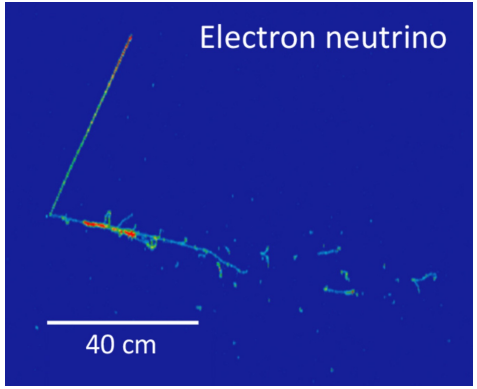
Engine for advances in neutrino physics, detector R&D, and theory

- 80 SBN-related papers and counting
  - Over 2800 citations

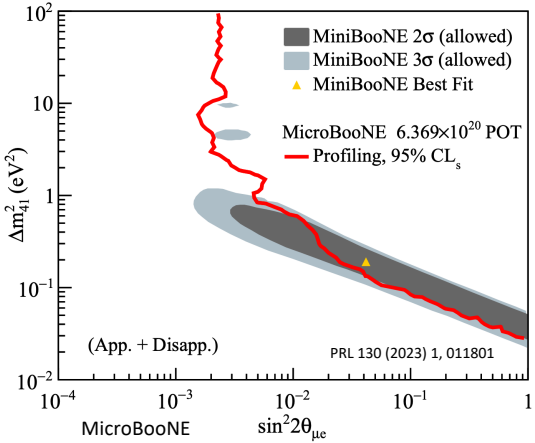
Establishing FNAL-based LArTPC community, training the next generation

Results and discoveries from the current SBN program will inform future short-baseline neutrino physics program

SBND



ICARUS



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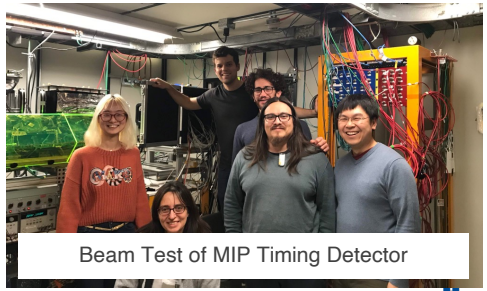
The Energy Frontier - The LHC and HL-LHC Program

Fermilab is committed to maintaining its **leadership** role in fully exploiting the LHC and HL-LHC programs along with our partner CERN, USCMS, and international collaborators.

- Make the next set of **groundbreaking discoveries** and high-precision measurements using the LHC and HL-LHC data with over 1000+ publications to date.
- Complete the HL-LHC **detector and accelerator upgrades.**
- Play a critical role in CMS **operations** through the end of HL-LHC. Be the driver of S&C innovation aimed at facing the challenges foreseen at the end of the decade.
- Enhance the CMS detector and **explore new opportunities** including proposed high η experiments
- Enable the community through hosting the USCMS Collaboration, the LHC Physics Center, and facilities for detector construction and software and computing.


Outer Tracker Module


Prototype HGCAL Cassette

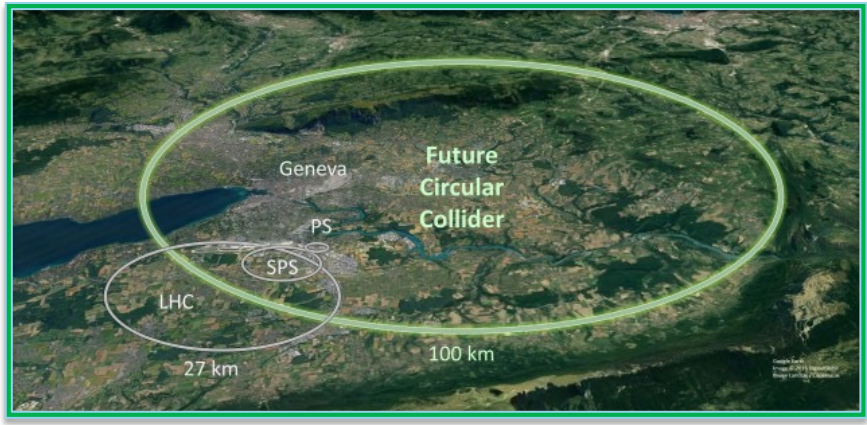

Beam Test of MIP Timing Detector

The Energy Frontier – Beyond the LHC and HL-LHC Programs

Precision measurements of the Higgs boson and EW sector and BSM searches at future colliders will shed light on key open questions in particle physics.

- This exploration will require an investment in accelerator technology research to
  - Contribute to the international effort to build a Higgs factory at CERN
  - Revitalize accelerator and detector R&D towards a next-generation multi-TeV energy frontier machine
  - Take advantage of emerging technologies
- *Fermilab is poised to host a next generation multi-TeV energy frontier collider, as a global endeavor, following the completion of DUNE*
- In order to make realistic progress, a substantial investment **in targeted accelerator research** as well as **associated detector research** will be required

These efforts should be organized through **national integrated accelerator R&D and detector R&D programs** that are aligned and coordinated with our international partners



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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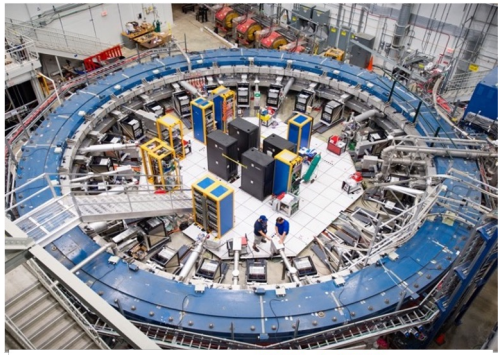
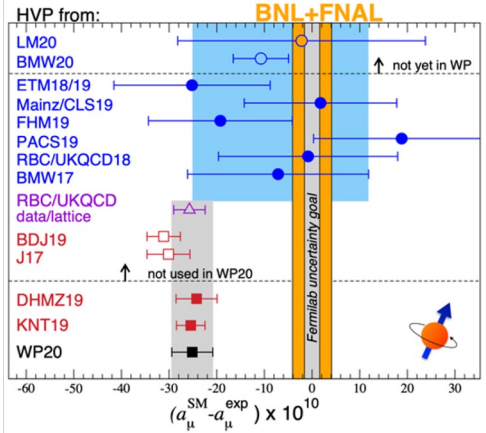
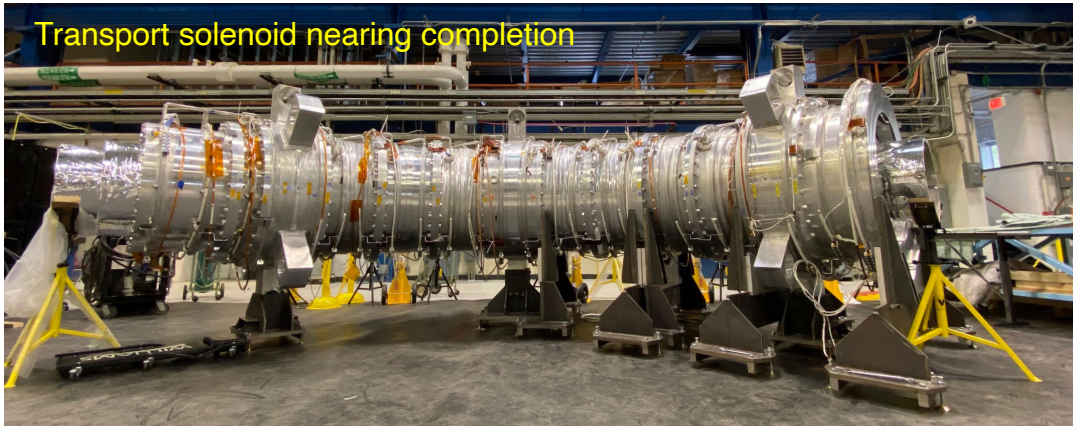
Muon program well underway at Fermilab

- FNAL's accelerator infrastructure is a key enabler of world-leading IF experiments such as Muon g-2 and Mu2e
- Muon g-2 just completed TDR goal collecting 21x BNL stats
- Mu2e experiment first physics run in 2026, prior to the long shutdown for LBNF construction
  - –Healthy transition from data analysis on g-2 to data taking on mu2e





Recent and ongoing results from g-2 expt. and theory community



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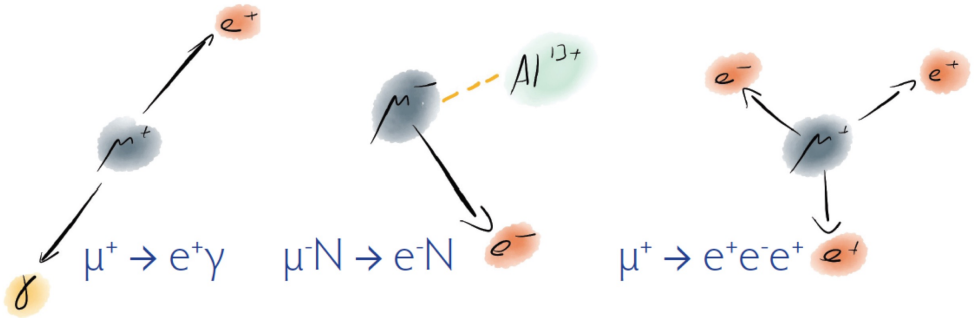
Muon Charged Lepton Flavor Violation for the Future

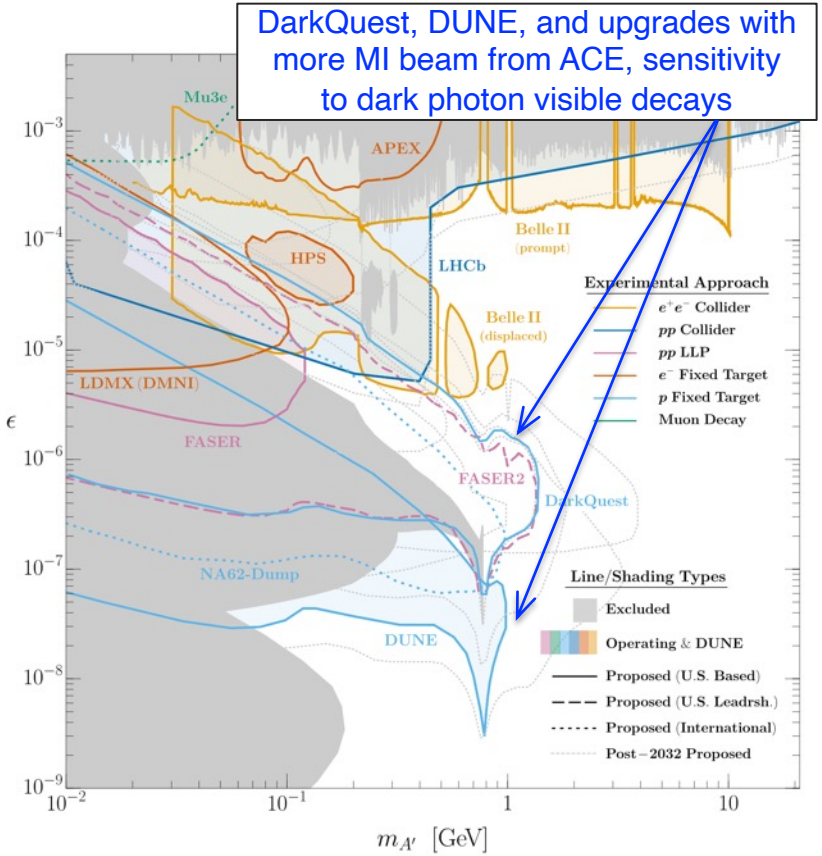
- Mu2e-II is designing for another 10x in sensitivity with direct injection of PIP-II beam
  - Relies on continuous wave capability of PIP-II
- Future muon experiments could leverage the PIP-II linac and ACE to power next-generation charged lepton flavor violation experiments
  - Up to 100x gains



- Precision muon experiments have synergies with muon collider R&D and Fusion Energy Science, including target design, rad-hard solenoids, and accumulation ring

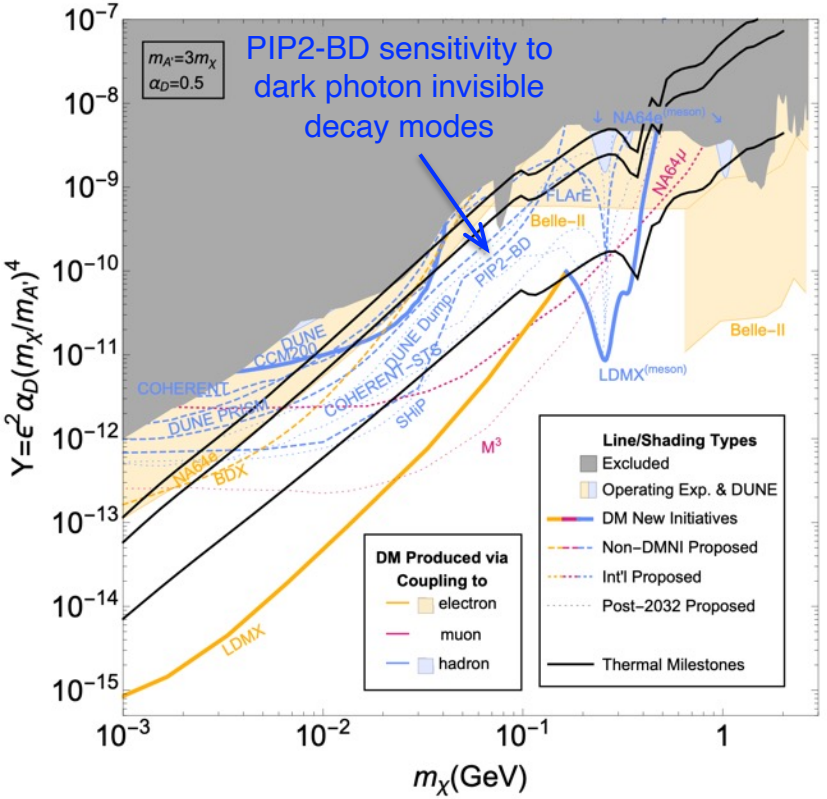
High Intensity Proton Beam to Explore Dark Matter Portals

- ACE will also enable excellent opportunities for accelerator-based dark sector searches at modest cost and scale
  - **At high energy**, proton beam dump searches can probe new parameter space making use of existing accelerator infrastructure and experiments (120 GeV beam)
  - At low energy, proton beam dump searches can form part of a new neutrino and dark sector facility that leverages the full power of the PIP-II beam coupled to an accumulator ring



High Intensity Proton Beam to Explore Dark Matter Portals

- New FNAL accelerator infrastructure will also enable excellent opportunities for accelerator-based dark sector searches at modest cost and scale
  - At high energy, proton beam dump searches can probe new parameter space making use of existing accelerator infrastructure and experiments
  - **At low energy**, proton beam dump searches can form part of a new neutrino and dark sector facility that leverages the full power of the PIP-II beam coupled to an accumulator ring (2-8 GeV beam)



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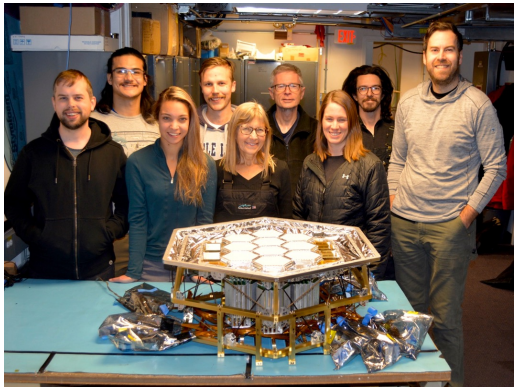
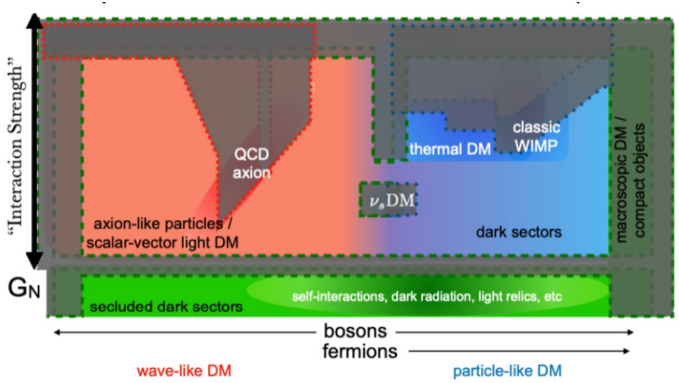
Cosmic Science

- The Cosmic Frontier addresses fundamental questions by connecting the very small to the very large:
  - **What is the dark matter?**
  - **What is dark energy?**
  - **What is the physics of inflation?**

Aim high, search wide, delve deep



SPT-3G Focal Plane at the South Pole



Dark Matter Parameter Space

Fermilab roles capitalize on unique strengths, core infrastructure, detector development support, facilities, and large talent pool

- Technical capabilities built up from accelerator program are applicable to Cosmic, including **largest HEP investment in detector development**
- **Large pool of engineers and technicians**, all available to User community

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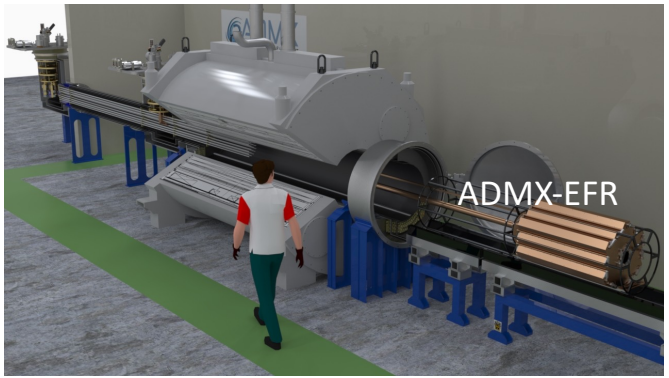
Cosmic Science at Fermilab in the Coming Decade

Operating Projects in the next decade include **Rubin LSST/DESC** and **SuperCDMS**

The highest priority future Cosmic Frontier effort at Fermilab in the next decade is **CMB-S4**

Other important projects are Axion DM (ADMX-EFR), Sub-GeV DM (Oscura), Dark Energy (Spec-S5)

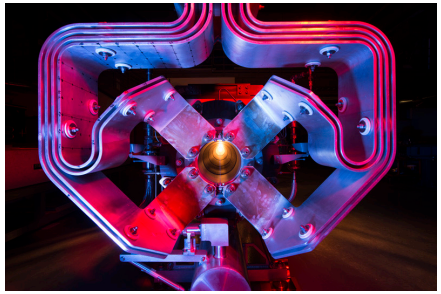
- **Partner with other labs and universities** to deliver the next generation of small projects
- Fermilab will **explore opportunities to build an axion center** with large magnets to serve the dark matter experimenter user community



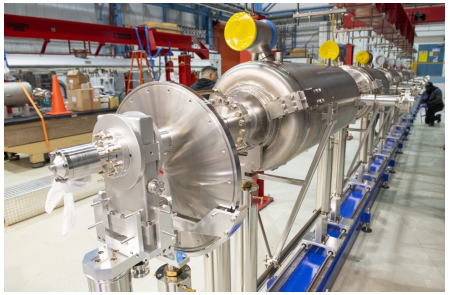
Accelerator Science and Technology

General Accelerator R&D: GARD Program

- Fermilab R&D under GARD has resulted in enabling advances for HEP



MW-Targets for LBNF



High Q SRF for PIP-II

Nb_3Sn magnets for HL-LHC

- Fermilab's key accelerator science & technology areas include SRF, magnets, targets, accelerator & beam physics; R&D is guided by GARD roadmaps
- Continued progress towards changing the cost/capability curve is key for the next generation of accelerators

Accelerator Science and Technology

Proposed: National Integrated Accelerator and Detector R&D Program on Future Colliders

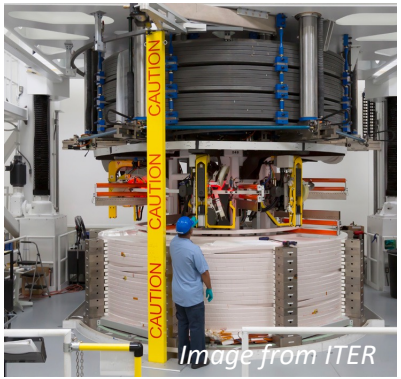
- Proposed future colliders include accelerator technologies that are not currently covered by GARD program but require substantial R&D
- **Accelerator R&D Program on Future Colliders** to provide new, targeted funding to solve technical challenges for new machines

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

July 14, 2022

U.S. National Accelerator R&D Program on Future Colliders

P.C. Bhat[1,†], S. Belomestnykh[1,5], A. Bross[1], S. Dasu[6], D. Denisov[4], S. Gourlay[7], S. Jindariani[1], A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[3], M.A. Palmer[4], T. Raubenheimer[3], V. Shiltsev[1], A. Valishev[1], C. Vernieri[3], F. Zimmermann[9]



Examples may include high field and large bore solenoids, prototype cryomodules for FCC-ee, and accelerator lattice design studies

Also benefits cosmic, quantum, BES, NP, industry…

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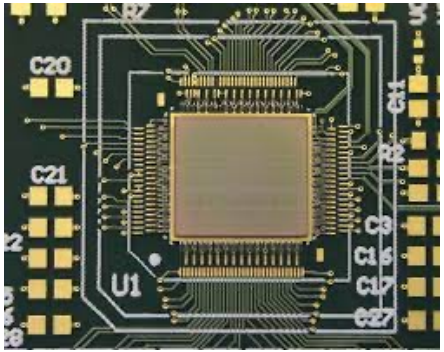
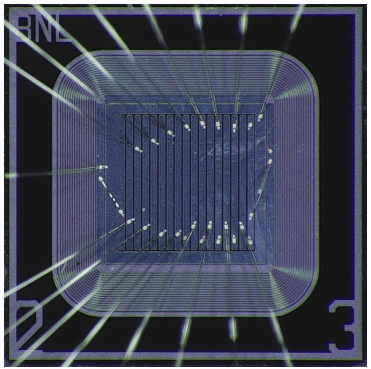
Detector R&D

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

- **Fermilab enables targeted R&D including**
  - DUNE
    - Targeted R&D for Far Detectors 3 and 4, building on recent R&D that led to FD 1 and 2
    - Short baseline
    - Near detector
  - Future Collider Detectors – coordinating with international partners
    - Silicon tracking including picosecond timing and low-mass
    - 5D and dual readout calorimetry
    - Synergies between e+e- and muon collider requirements
- **Fermilab enables blue-sky R&D**
  - Addressing four grand challenges of the DOE Detector and Instrumentation Basic Research Needs
  - Opening roads to ground-breaking technologies





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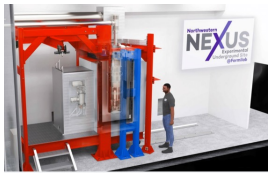
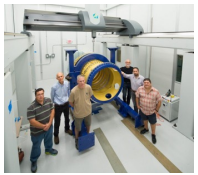
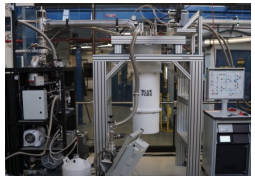
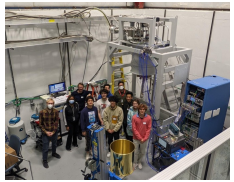
Fermilab Facilities Enable Advances

- **Fermilab facilities enable advances**
  - Helen Edwards Engineering Research Center
  - Test beam and irradiation facility
  - Micro- and macro-packaging and testing
  - Noble element detector facility
  - Scintillators: unique HEP facility with high demand





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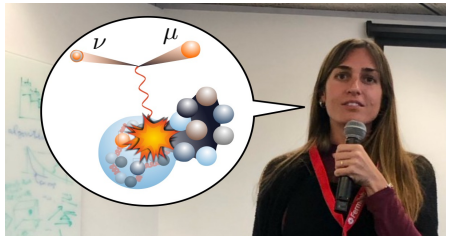
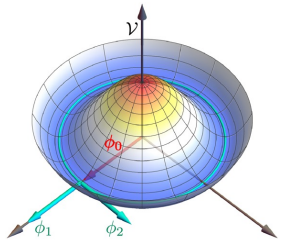
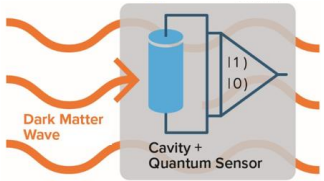
US HEP Theory

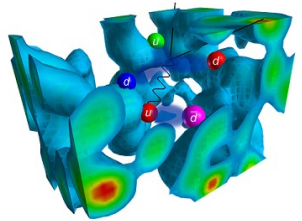


Fermilab is committed to providing critical theory needs of the HEP program in the coming decade, through both in-house efforts and consortia with universities and other labs:

- Further ramp up **theory support for DUNE and the ongoing neutrino program** to maximize the physics output, as was done for the LHC
- **Invigorate theory initiatives** to explore the frontiers of the **HL-LHC reach** and stimulate **a future collider program worldwide**
- Develop a **coordinated theory effort** towards shaping a broader **dark matter and dark sector search** program
- Guide the interpretation of precision **multi-messenger cosmology** data
- Continue expanding the scope and capabilities of **lattice gauge theory** to meet the needs of the HEP experimental program







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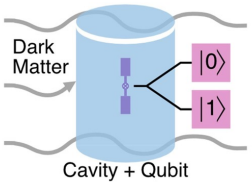
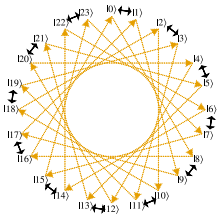
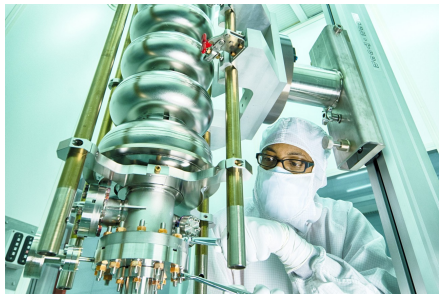
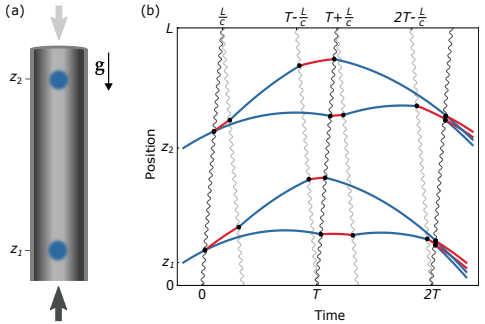
Quantum

- **Quantum science and technology at Fermilab is growing**
  - **Quantum for HEP** and **HEP for Quantum**
  - **Host of the SQMS National Quantum Initiative Center**
    - Record-breaking systems for quantum computing and sensing
  - Strong presence in **ORNL-led Quantum Science Center**
    - Leading in quantum sensors
  - **MAGIS 100** (gravitational wave and dark matter searches)
  - **Quantum theory**
  - **Control and readout electronics**









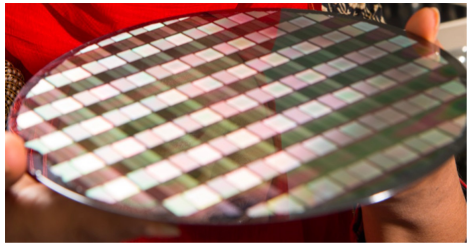
- In the coming years Fermilab will deploy its first quantum computer onsite, develop quantum sensing opportunities, advance quantum networks research, and advance quantum simulations of QFT.

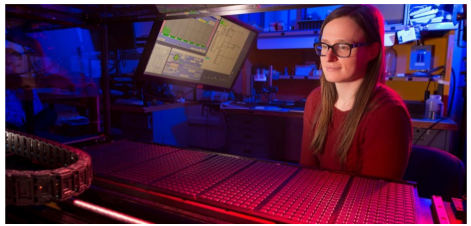
Microelectronics

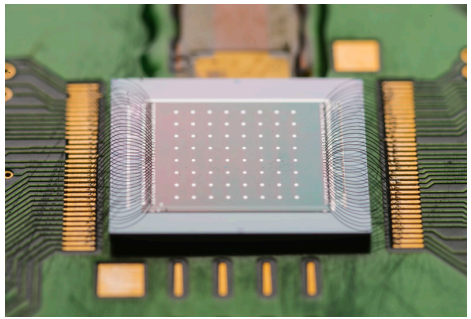
Fermilab, together with other national labs, academic and industry partners, wants to **establish and co-lead a major US Microelectronics Co-design center**

Future Detector Development heavily relies on advances in microelectronics

- Support the community for **extreme environment microelectronic development**
- Further advance expertise in **state-of-the art integrated circuit design and testing** to enable precision science measurements
- Further develop **Collaboration and Partnerships** to leverage and advance transformative technologies
  - Cross Office of Science partnerships to enable co-design with new materials (BES), novel algorithms (ASCR), energy efficient processes (EERE)
  - Across federal government collaboration with NASA, DARPA, DOD enabled by the CHIPS act
  - Engage with industry on production scale processing, heterogeneous integration and advanced packaging solutions







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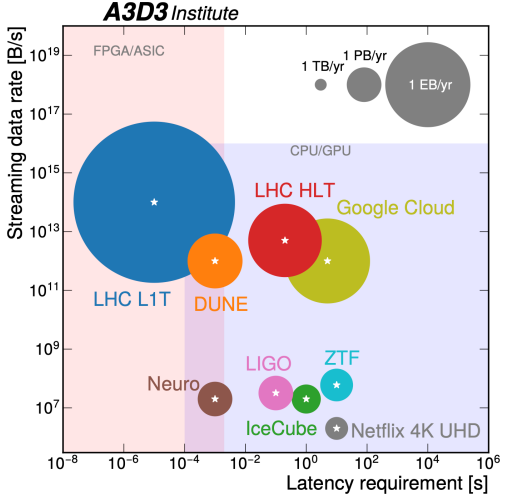
Computing & AI

- HEP faces **unique** high-throughput computing challenges from **massive data rates**
- Advanced computing techniques
  - Enable deeper insights and improve performance
  - Improve operational efficiency
  - Ultimately accelerate time-to-physics and discovery



Support formation of
Coordinating Panel for Software and Computing
to promote, coordinate, and assist in developing HEP software & computing community

Evolve HEP computing infrastructure
Storage technologies, analysis facilities, heterogeneous computing (e.g. GPUs)

Leverage multidisciplinary computational & domain science expertise
Federal HPC facilities and commercial cloud, specialized services, modern software stacks

Embrace AI/ML for HEP and also HEP for AI/ML
Develop AI capabilities for HEP science, support HEP contributions to broader AI advances

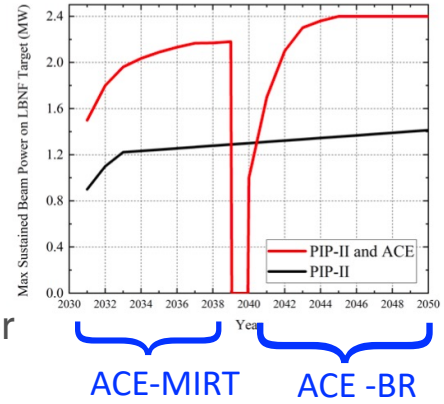
Fermilab and the Accelerator Complex Evolution (ACE)

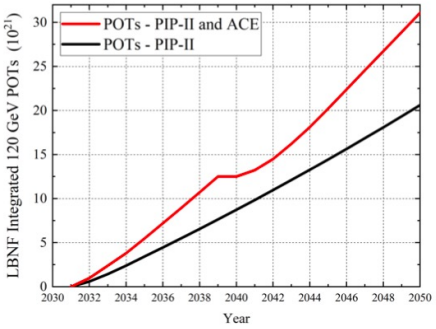
- ACE has two components
  - Main Injector Ramp and Targetry (**ACE-MIRT**)
    - Increases the beam to DUNE Phase I
      - **Capability**
    - Upgrades components
      - **Reliability**
  - Booster Replacement (**ACE-BR**)
    - Achieves DUNE/LBNF Phase II goal of 2.4 MW
      - **Capability**
    - Provides beam for a physics program beyond DUNE
      - **Capacity**
    - Fixes the bottleneck in the future Fermilab complex
      - **Capacity and Reliability**

Capability
Capacity
Reliability

Main Injector Cycle Time Reduction

- Why
  - More beam to DUNE
    - Plan includes completing Mu2e
  - Reliability
    - Replace aging equipment in the Main Injector
- What





		PIP-II Booster Intensity		
Scenario	**Present**	**PIP-II**	**A**	**B**
MI 120 GeV ramp time (s)	**1.333**	1.2	**0.9**	**0.7**
Booster intensity (10^{12})	**4.5**	6.5		
Booster ramp rate (Hz)	15	20		
Number of batches	12	12		
MI power at 120 GeV (MW)	0.865	1.25	1.666	**2.142**

Booster Replacement Addresses Fundamental Limitations

- Why?
  - There are **fundamental limitations** in operating the Booster in the ACE era:
    - The Booster cannot handle > 1% of PIP-II beam
      - 6.5E12 PPP absolute maximum
    - The Booster cannot support > 2.1 MW from the Main Injector
    - **The Booster cannot support DUNE and any other >= 8 GeV physics program simultaneously**
    - Radiation losses
      - e.g., at transition - no upgrade can alleviate this
    - Tunnel too restrictive - size, depth

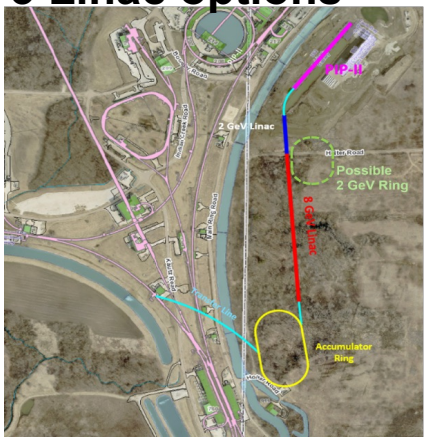
Fermilab needs a Booster replacement in order to enable a physics future in addition to DUNE as well as to meet the design goals of DUNE/LBNF

What: Replacing the Fermilab Booster

- Proton Intensity Upgrade Central Design Group (PIU-CDG)
  - Chartered by Director Merminga at the same time as the Science Priorities Working Group
  - Led by Steven Brice and Brenna Flaugher
  - Charged with doing a preliminary exploration of Booster replacement options to support the future Fermilab facility

3 RCS options

3 Linac options



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Physics Potential of the Fermilab Complex with the Booster Replacement

- Physics opportunities at 800 MeV, 2 GeV, 8 GeV, and 120 GeV
- Many sources of discussion
  - Snowmass
  - P5
  - Multiple workshops held
    - **Physics Opportunities Beam Dump Facility at PIP-II and Beyond Workshop**
    - **ACE Science Workshop series**
    - others, e.g., “Workshop on a future muon program at Fermilab”
- Provides beam for accelerator research

Need to start now in order to enable physics in the late 2030s!

Conclusion: Vision for the Fermilab Facility

- The Accelerator Complex Evolution
  - **ACE-MITR**
    - Capability
      - DUNE to achieve world-leading results on an accelerated schedule
    - Reliability
      - Replace aging portions of the Fermilab Accelerator Complex
  - **ACE-BR**
    - Capability
      - To Realize the DUNE Phase II design goals
    - Capacity
      - Provide beam for a rich physics program beyond DUNE
      - Respond to new ideas in the coming decades
    - Reliability
      - Ensure a robust platform for the future of the complex

Conclusion: Vision for US Particle Physics

- With our international partners, realize the full scope of the **best-in-class DUNE experiment** in a timely fashion
- With our international partners, participate as strong contributors in the **LHC and HL-LHC**
- Lay the foundation for an **international Higgs factory** and a **next-generation multi-TeV collider**
- Enable the accelerator complex to **probe the unknown** with a broad, balanced, diverse, discovery program
- Uncover the mysteries of the universe with **CMB-S4 and dark sector initiatives**
- Engage in enhanced **Accelerator R&D, Detector R&D,** and **Theory** efforts to enable the science
- Excel in National Initiatives in **Microelectronics, QIS,** and **AI/ML**

Engage, train, and support a **diverse community**