

DOE High Energy Physics Report to HEPAP

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U.S. DEPARTMENT OF
ENERGY

Office of
Science

[Energy.gov/science](https://www.energy.gov/science)

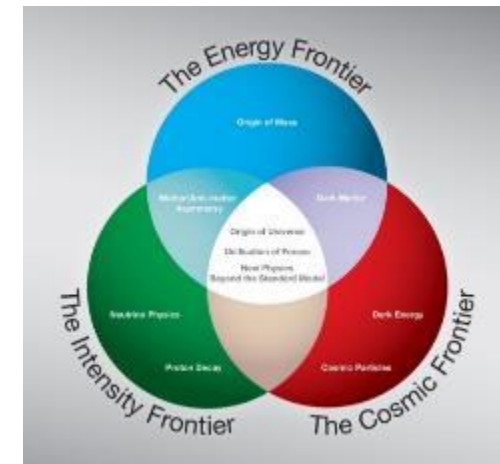
HEP Research and Technology



Colliders to the Cosmos

Spans the breadth of three “frontiers”:

- Energy Frontier
- Intensity Frontier
- Cosmic Frontier



2008 P5

Plus cross-cutting themes

- Theoretical physics
- General Accelerator and Detector R&D
- Computational HEP and AI/ML
- QIS Research and Microelectronics

Office of High Energy Physics at a Glance

FY 2023 Enacted: \$1.166B



Largest Supporter (~85%) of Particle Physics in the U.S.



Funding at >160 Institutions, including 12 DOE Labs



Over 1,175 Ph.D. Scientists and 525 Grad Students Supported



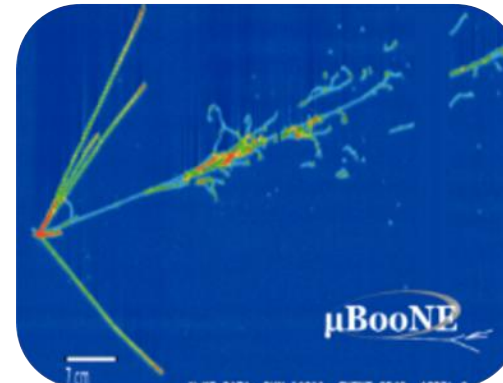
Over 2,325 Users at 2 SC Scientific Facilities



Facility Operations: 29.7%, \$346.6M



Projects: 30.4%, \$355M



Research: 39.8%, \$464.4M



~30% of Research to Universities

HEP Budget (\$K): Research, Facilities/Ops, Projects

FY 2014 – FY 2023

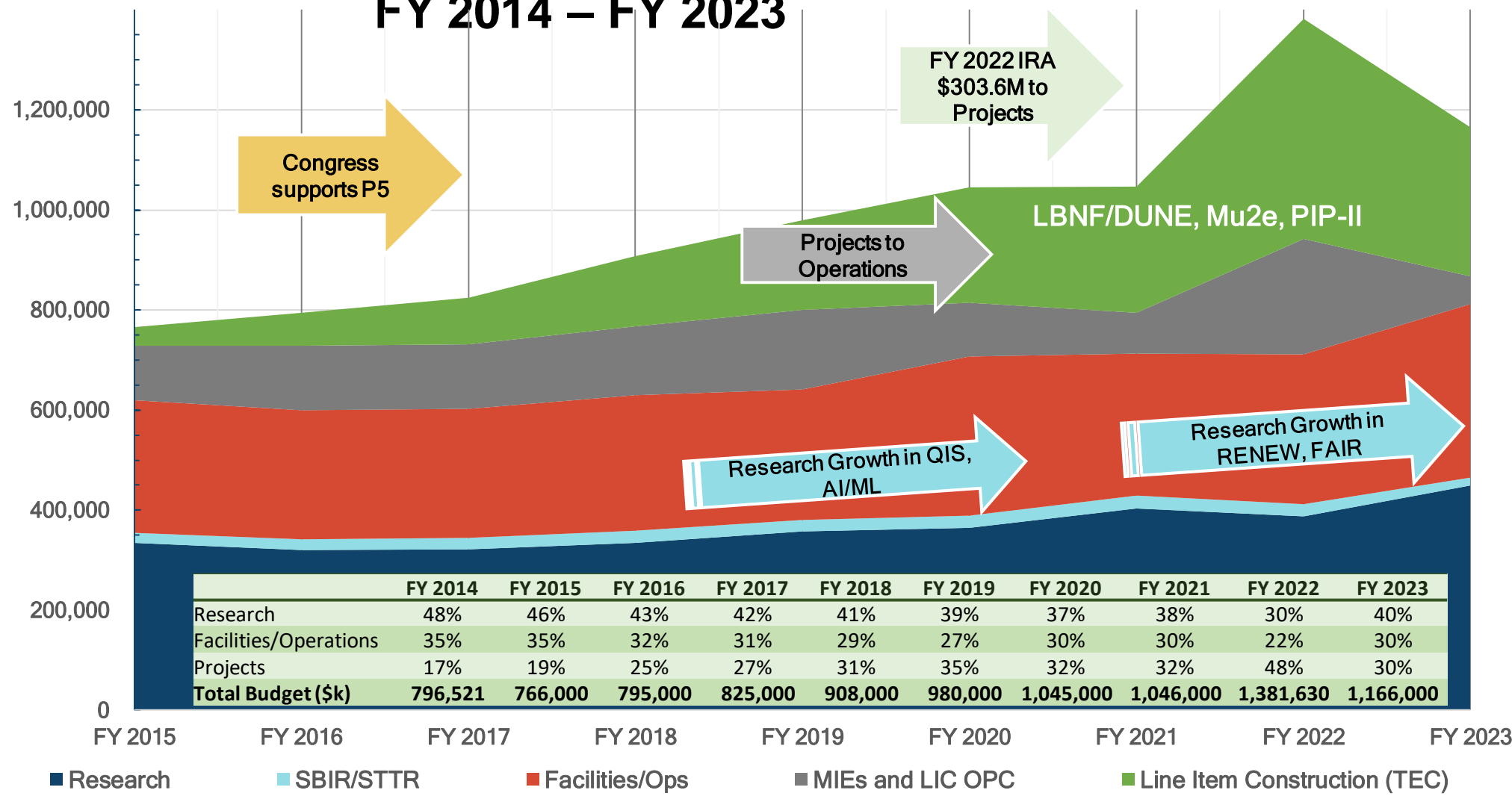


Strategic Plan for U.S. Particle Physics next 10 years

Particle physics is global

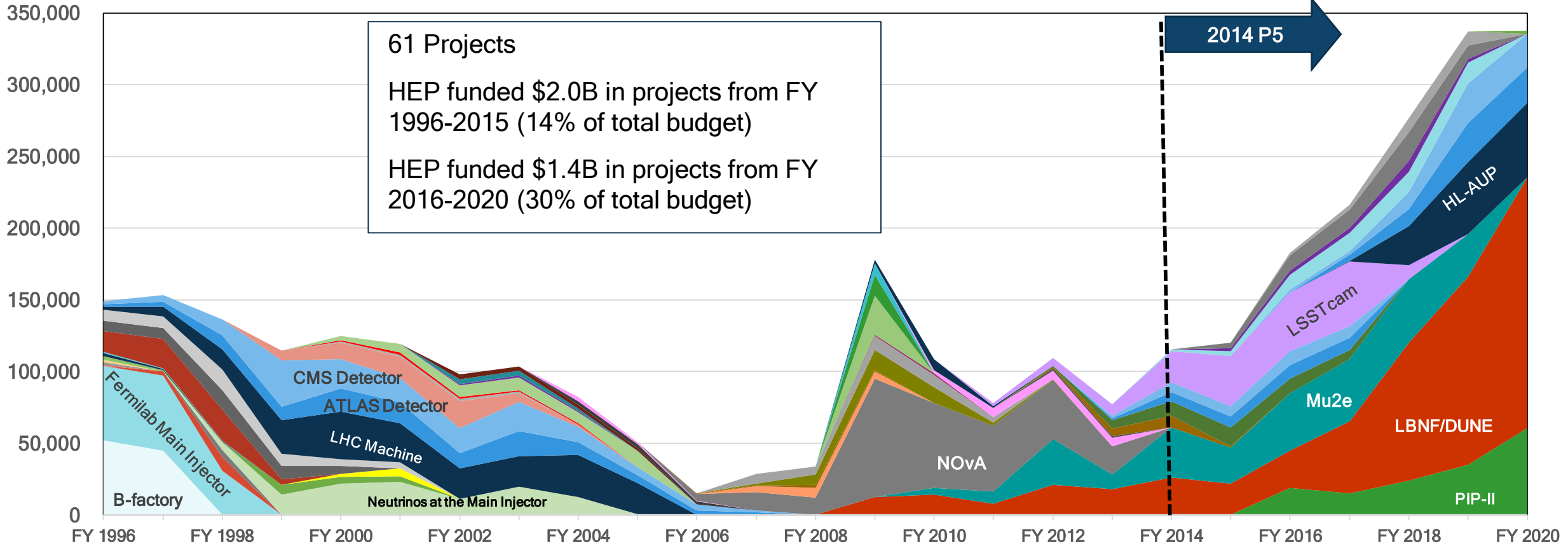
Community made difficult choices

Increase investment in construction



Historical Chart of HEP Projects

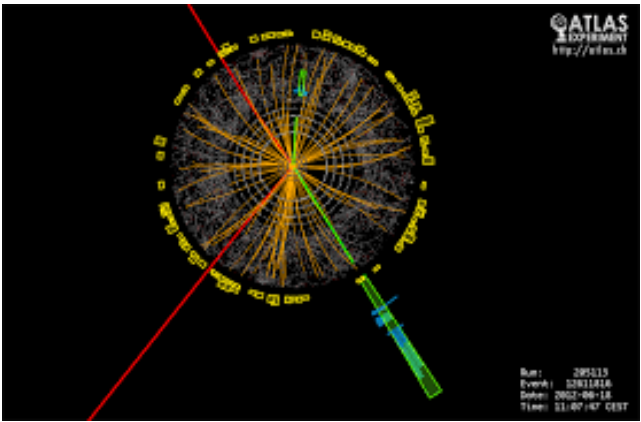
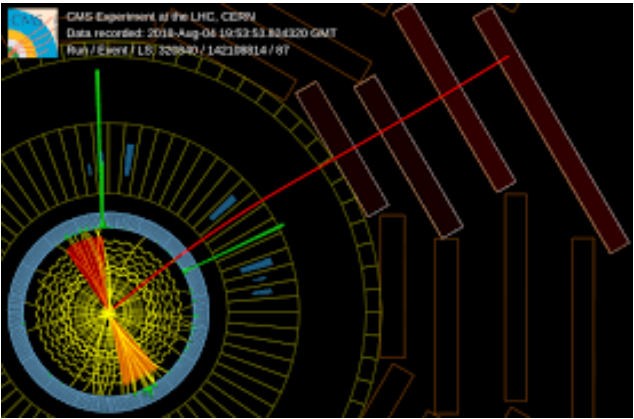
FY 1996 – FY 2020



- | | | | | | |
|---------------------------|--------------------------|-----------------------------------|---------------------------------|--------------------------------------|---------------------|
| ■ B-factory | ■ Fermilab Main Injector | ■ SLAC Master Substation Upgrade | ■ C-Zero Area Experimental Hall | ■ Neutrinos at the Main Injector | ■ Willson Hall Reno |
| ■ SLAC Research Office | ■ PIP-II | ■ LBNF/DUNE | ■ Mu2e | ■ PIP-III | ■ LBNF Hi-Flux |
| ■ Mu2e Upgrade | ■ Future Collider | ■ Rare k-decay Experiment | ■ KTeV Experiment | ■ Next Linear Collider Test Facility | ■ g-2 |
| ■ Antimatter in Space | ■ Super-K | ■ BaBar | ■ CDF Upgrade | ■ D-Zero Upgrade | ■ LHC Machine |
| ■ ATLAS Detector | ■ CMS Detector | ■ MINOS | ■ AMS Upgrade | ■ CDMS | ■ GLAST/LAT |
| ■ Auger | ■ Run IIb CDF Detector | ■ Run IIb D-Zero Detector Project | ■ VERITAS | ■ BaBar Upgrade | ■ NOVA |
| ■ MINERvA | ■ T2K | ■ Daya Bay | ■ DES | ■ SuperCDMS at Soudan | ■ BELLA |
| ■ FACET | ■ Cryogenic Refrigerator | ■ MicroBooNE | ■ HAWC | ■ Belle II | ■ Muon g-2 |
| ■ LHC Accelerator Upgrade | ■ LHC ATLAS | ■ LHC CMS | ■ LSSTcam | ■ HL-AUP | ■ HL-LHC-ATLAS |
| ■ HL-LHC-CMS | ■ LZ | ■ SuperCDMS | ■ DESI | ■ FACET-II | ■ CMB-S4 |
| ■ FACET-II Upgrade | | | | | |

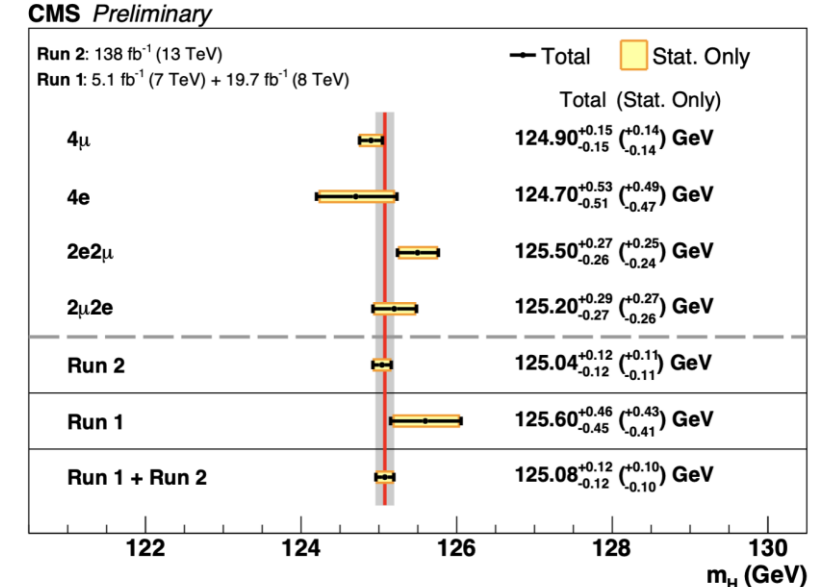
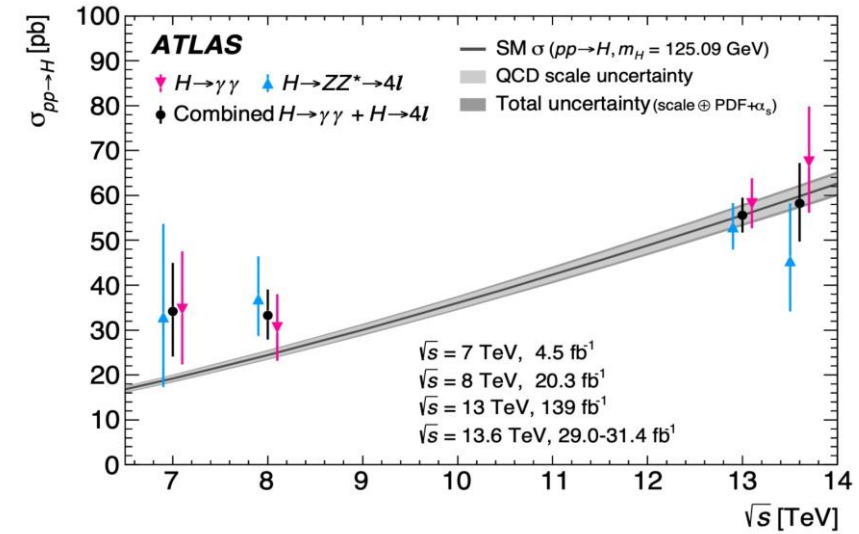
Energy Frontier: Large Hadron Collider Experiments

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●



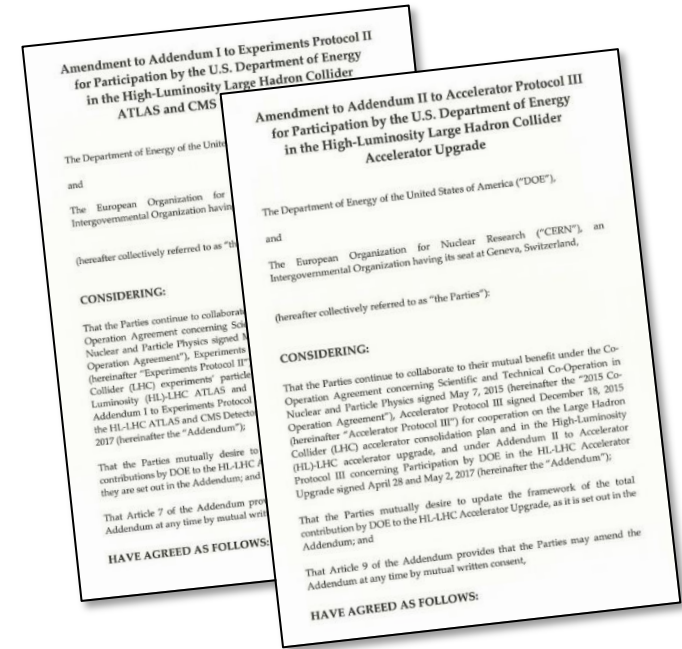
Energy Frontier Program - the LHC and Higgs Science Driver

- ATLAS and CMS collaborations continue to lead HEP with physics results, now together with over 2,480 publications in peer-reviewed journals since data taking began at the LHC in 2009**
 - Strong showing with excellent new results presented throughout the 2023 conferences and workshops
- Representative highlights include initial Run 3 results of the Higgs boson**
 - Run 3 commenced in 2022 at a higher center-of-mass energy of 13.6 TeV
 - Expect 6% increase of Higgs cross section at 13.6 TeV, driven by gluon fusion
 - Important validation by ATLAS of the Run 3 data
- Precision measurement of the Higgs mass by CMS**
 - H \rightarrow 4-leptons decay channel using the full Run 2 LHC dataset
 - $M_H = 125.08 \pm 10$ (stat) ± 0.05 (syst) GeV
 - Most precise single channel measurement to date!



Energy Frontier Program - HL-LHC Upgrade Projects

- Amendments to the 2017 DOE-CERN Addendum agreements for DOE's contributions to the HL-LHC accelerator and detector upgrades signed by DOE (H. Kung) and CERN (F. Gianotti) on October 4, 2023
 - Reflect the updated total project costs to DOE's HL-LHC Accelerator and the HL-LHC [Phase-II] ATLAS and CMS detector upgrade projects ⇒ following the CD-2 baseline (ATLAS, CMS) and re-baseline (accelerator) reviews and approvals
- U.S. HL-LHC Accelerator Upgrade Project's 1st cryo-assembly shipped to CERN
 - Represents the first deliverable from the U.S. to the HL-LHC Accelerator



HL-LHCAUP: Cryo-assembly Shipment to CERN (at Fermilab)

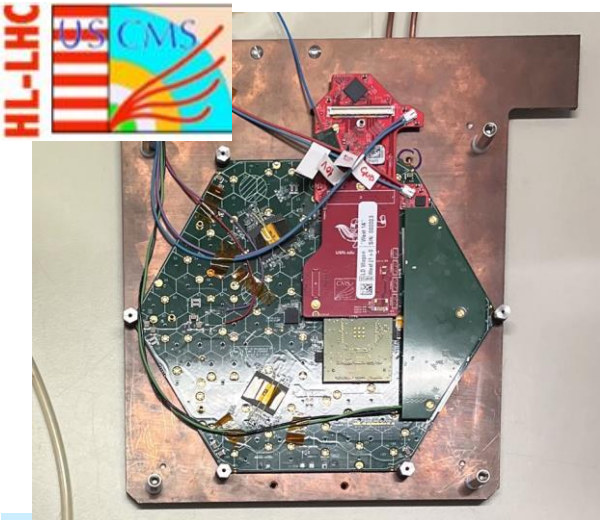


High Luminosity LHC Upgrade Projects

- **U.S. HL-LHC Accelerator Upgrade Project progressing well**
 - Project was re-baselined by DOE in March 2023 to account for impacts from COVID, inflation, and supply chain issues
 - Total project cost increased from \$242M to \$266M
- **U.S. HL-LHC [Phase-II] Detector Upgrade Projects baselined (CD-2) by DOE in Jan 2023 (ATLAS) and Mar 2023 (CMS)**
 - 5 DOE national labs and over 65 U.S. universities delivering major portions of the detectors, now moving into production
 - Total project cost for each ATLAS and CMS upgrade at \$200M, takes into consideration impacts from COVID,



High Luminosity LHC Upgrade Projects



CMS Silicon sensors and onboard electronics assembled for radiation testing.

The three U.S. HL-LHC Projects are at the fabrication stage or soon will be.

- All fabrication sites are at full speed.
- The ATLAS and CMS projects are delivering the final prototypes for approval.
- The Accelerator Upgrade team has just delivered the 1st of the 10 quadrupole



ATLAS Inner Tracker Outer Cylinder supporting frame of Forward Survey



The AUP group at FNAL with the magnet assembly after the first ever successful testing of the technology.



Dr. Kung singing the assembly before its voyage.

Arrived at CERN On Nov 28.



Intensity Frontier Experiments

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●



ICARUS at Fermilab



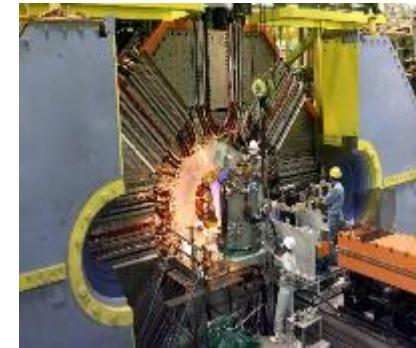
Mu2E at Fermilab



NOvA at Fermilab and Ash



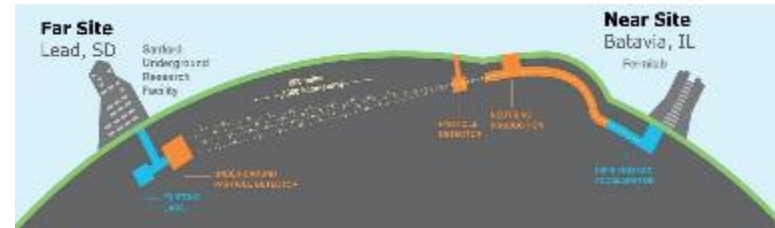
Muon g-2 at Fermilab



Belle II at KEK, Japan



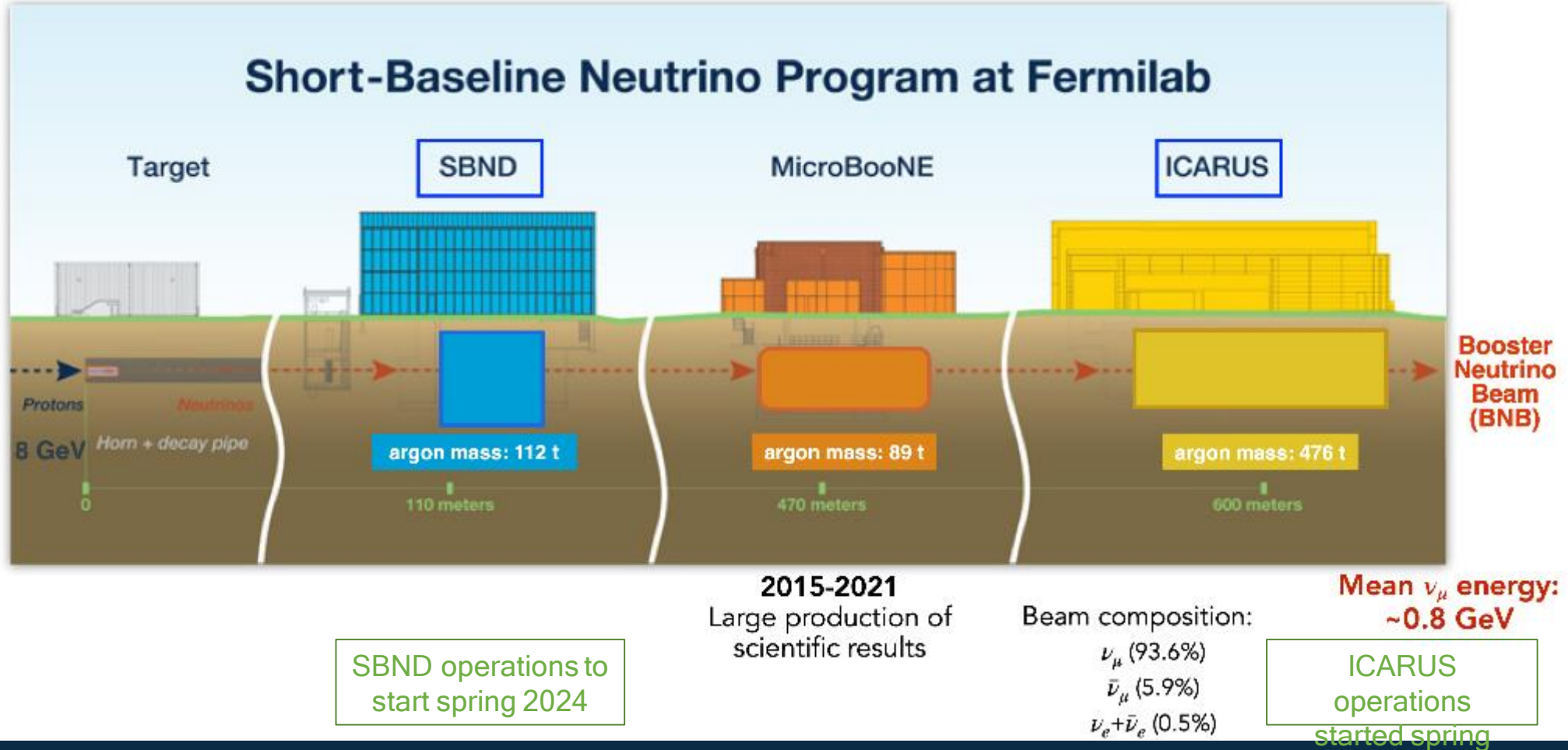
COHERENT at ORNL



DUNE at Fermilab and Lead,

Short Baseline Neutrino Program

- SBN addresses the 2014 P5 recommendation for experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.



Short Baseline Neutrino Program

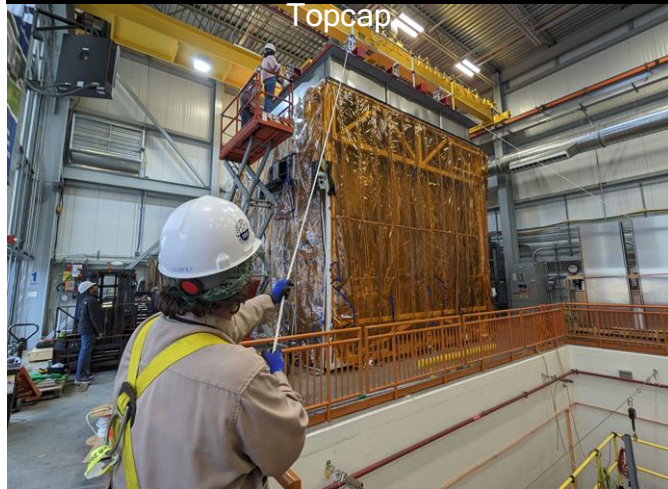
SBND 2023: detector installed, cryogenics installed, and cryogenics commissioning started

Dec 1, 2022 Detector at SBN



Full detector QC test after each step

February: Detector attached to cryostat

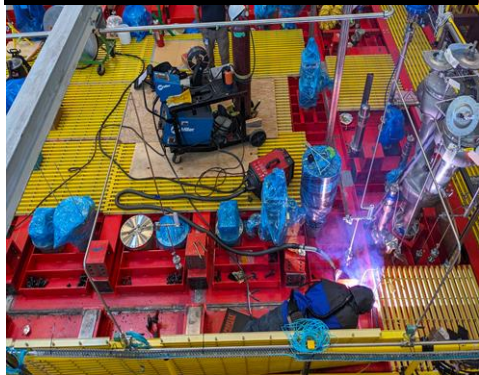


April 25: Detector installed in cryostat



View from camera inside cryostat

July: Cryostat Topcap Welded



October: Cable Routing Complete



Cryogenics commissioning started:

- ✓ LN2 and LAr Dewars full
- ✓ Cryostat pressure test (250mbarg)
- ✓ Valve and pump checkout

Next steps:

- Dec: complete cryogenics checkout
- Jan: GAr purge and cooldown
- Jan-Feb: LAr fill
- Feb-Mar: detector turn-on and full detector commissioning starts

Dec 1, 2023 welding last cryogenics line

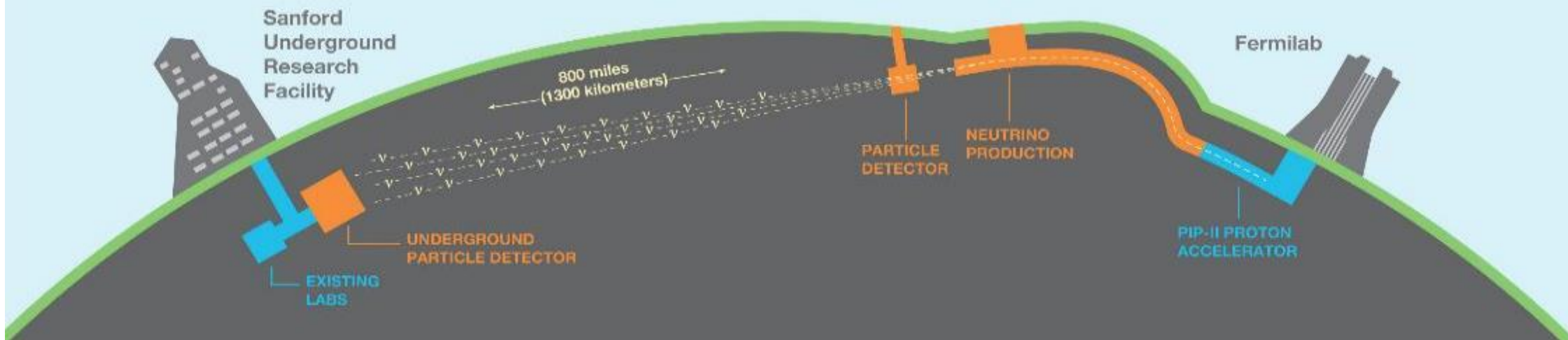


LBNF/DUNE: US Project Scope

Delivered at Two Sites through Five Subprojects

Far Site – SURF in Lead, SD
 Facility/Infrastructure and Far Detectors

Near Site – FNAL in Batavia, IL
 Facility/Infrastructure, Neutrino Beamline, and Near Detectors



Three subprojects

- ◆ FSCF-EXC - Far Site Excavation
- ◆ FSCF-BSI - Far Site Building & Site Infrastructure
- ◆ FDC - Far Detectors and Cryogenic Infrastructure

Technically limited schedule

Two subprojects

- NSCF+B - Near Site Conventional Facilities + Beamline
- ND - Near Detectors

Funding limited schedule

Largest DOMESTIC project in Office of Science (TPC = \$3.2B)

International HEP - Multi-Institutional DUNE MOU

- Memorandum of Understanding (MOU) between Fermilab - the host laboratory for DUNE - and the international partners collaborating on the experiment
 - Partners include CERN, Brazil, Canada, Czech Republic, France, Italy, Spain, and the United Kingdom
 - Memorializes the organizational, institutional, and financial framework for the shared execution of the DUNE program
 - Annexes to the MOU memorialize the associated partners' contributions to DUNE program's Far Detectors 1 and 2
- **Drafting of the MOU began in 2018, cooperatively by the DUNE collaboration, Fermilab, and DOE**
 - Dedicated DOE MOU Working Group to facilitate its preparation and the relevant DOE approvals that authorize Fermilab to sign with the partners
- **MOU signed on November 17, 2023, during the DUNE Resources Review Board (RRB) meeting at Fermilab**



North Detector Cavern & Central Utility Cavern

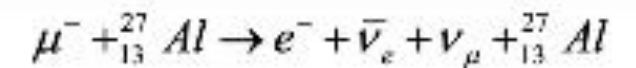
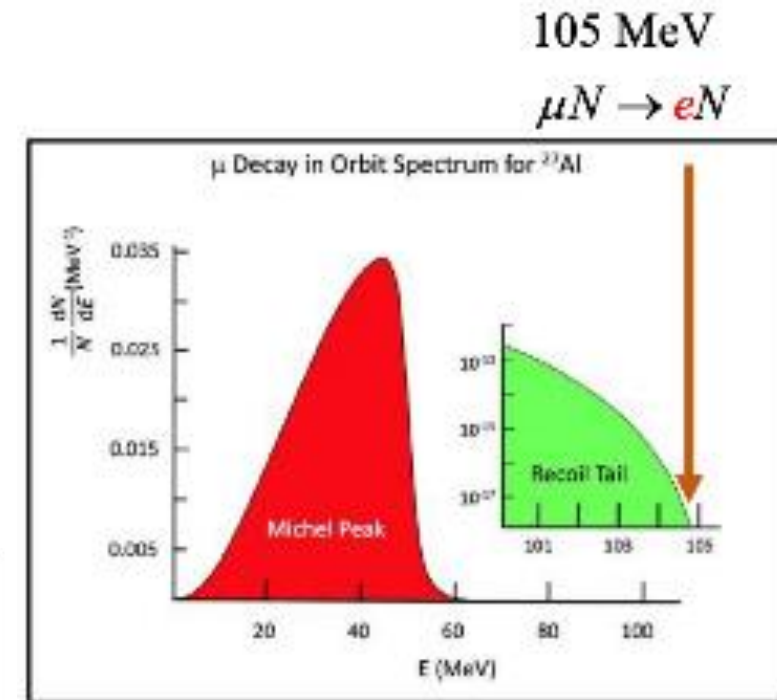
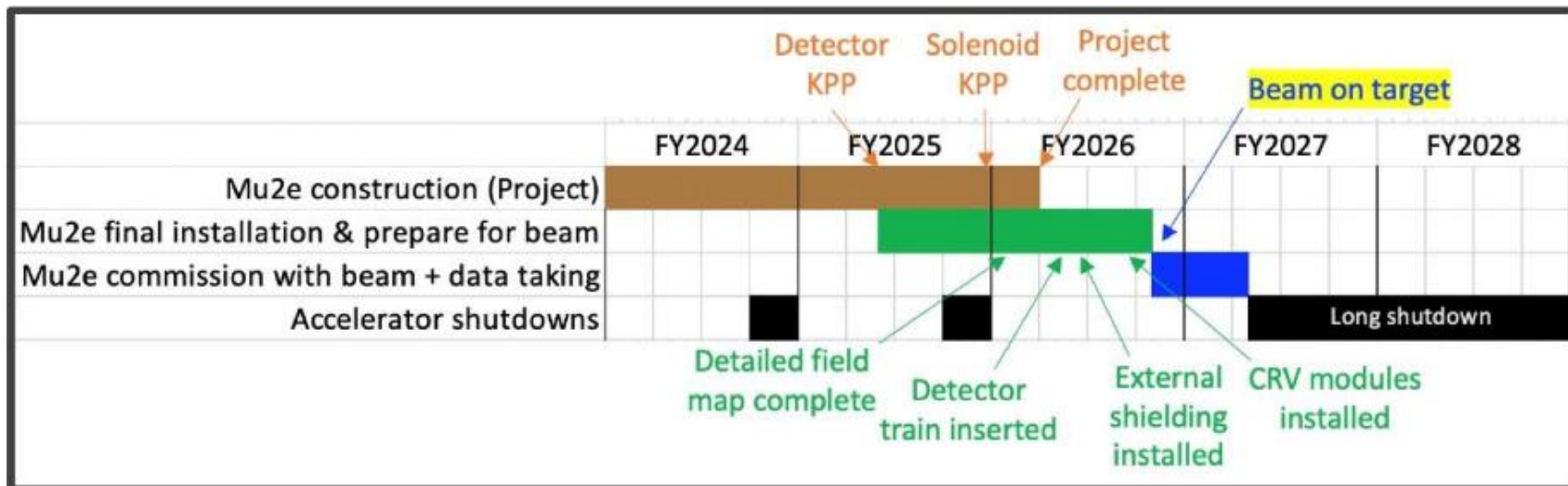


Far site excavation approaching 90% complete



FY 2023 HEP Intensity Frontier Highlights (Mu2e)

- Mu2e Project is fully funded and 90% complete
- Aiming for Project early completion date Dec 2025.
- Begin Run 1 data taking mid-CY2026 - about 6 months of data
- Goal: 10% of total data set and x1000 improvement in sensitivity over present experimental limit
- Resume after shutdown and take data for 4 more years.



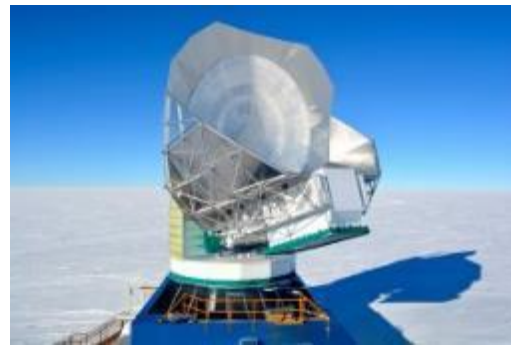
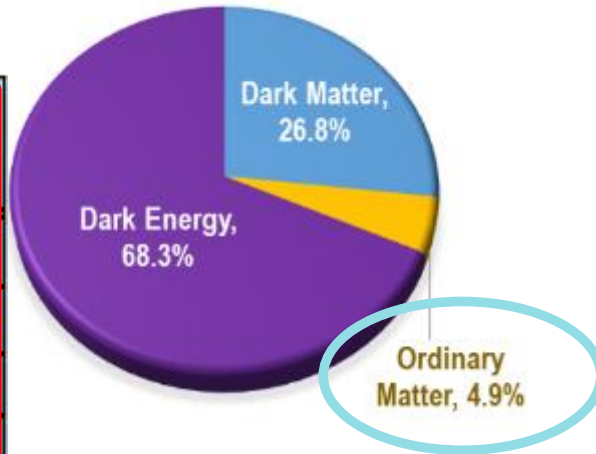
PIP-II Construction Project Highlights and Status

- ◆ New SRF Linac replacing 50-year-old infrastructure, increasing beam power, energy, reliability and upgradability for LBNF and other opportunities.
- ◆ Acquisition approach includes in-kind contributions of deliverables from international partners with world-leading expertise and capability, equivalent to \$300M in addition to the DOE TPC of \$978M. Project completion is forecast in FY 2033.
- ◆ Joint statement by India and U.S. in June 2023 hailed in-kind contribution from DAE for collaborative development of PIP-II for Long Baseline Neutrino Exp't.
- ◆ The cryoplant building at Fermilab for PIP-II is ready to receive the cryoplant when it arrives from Air Liquide as an in-kind contribution by India.
- ◆ Civil construction of the linac facility was halted May 25 due to a serious injury accident and is restarting now following conclusion of accident investigations and implementation of improved safety protocols.
- ◆ Schedule recovery and improvement plans are being implemented.

Cosmic Frontier Experiments

- **Cosmic Frontier experiments** address four of five science drivers
- They use naturally occurring sources to determine the fundamental nature of matter, energy, space and time.

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●



- Partnerships w/NSF (PHY, AST, OPP) NASA (AST, ISS, CLPS) are essential

Science Driver: Dark Matter

- ◆ DM-G2 (Generation 2) suite of experiments recommended by 2014
 - Complementary WIMP searches - SuperCDMS (Integration & Test; full data taking starts 2025), LZ operating
 - Axion search - ADMX-G2 operating
- ◆ DMNIs - significant technology and theoretical progress since 2014 led to opening up the phase space for discovery
 - HEP is supporting 5 concepts to complete R&D and develop execution plans for WIMP, axion searches and accelerator searches
 - Process to move forward to project fabrication phase will need to be developed
- ◆ Dark Matter searches also using LHC, gamma-ray and imaging surveys, etc.



Science Driver: Cosmic Acceleration

- ◆ Dark Energy - suite of Stage 3 and 4 imaging and spectroscopic survey (stage 3 - BOSS/eBOSS, DES; Stage 4 - DESI operating, Rubin starts survey in 2025); community is planning the next steps (e.g. DESI-II, Spec-S5) - these are with NSF/AST
- ◆ Dark Ages - DOE/NASA LuSEE-Night project to put limits on the Dark Ages signal (and perhaps discover it) from the far side of the moon is in fabrication; launch in late 2025/early 2026
- ◆ CMB - as recommended by P5, HEP participates in gen 3 experiment (fabrication/operations of SPT-3G) and is developing CMB-S4 to study Inflationary era - with NSF/AST and NSF/OPP

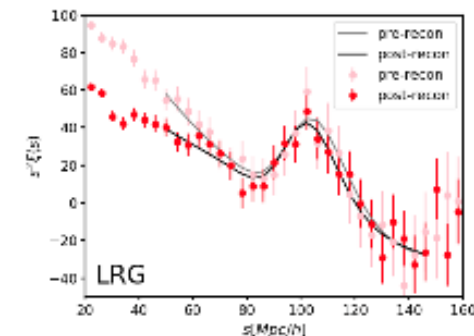
LSST Camera in test stand at SLAC.



LuSEE-Night will attempt first-of-its-kind measurements of the Dark Ages

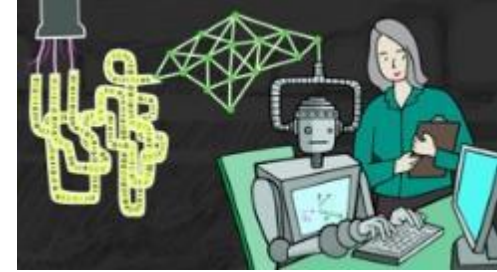


DESI BAO signal at 5sigma from first 2 months of data!



HEP Research Initiatives (from SC initiatives)

- ◆ QIS, AI/ML, Microelectronics, Advanced Computing, Accelerator Science and Technology, and ACCELERATE
- ◆ Quantum Information Science co-develops quantum information, theory, and technology with core research activities.
 - to more strongly focus and integrate efforts that align with HEP strengths in quantum sensors and theory
- ◆ AI/ML effort is highly embedded in core HEP research and accelerator technology, with a new thrust in proposal-driven, cross-cutting R&D. The balance between leveraging AI/ML tools for HEP science and using HEP data to drive AI/ML development will be reassessed.



Superconducting Quantum Materials and Systems Center

- SQMS is the largest DOE-supported QIS Research Center, hosted by Fermilab
 - Brings together over 500 collaborators across 34 institutions from academia, DOE national labs, and industry
- Today, within first 3-years, over 165 publications by SQMS researchers (peer-reviewed journals + ArXiv)
 - Just in FY 2023, published 50 journal papers
- Reviewed strongly at the Mid-term Progress Review, held by DOE in Feb-Mar 2023 for all 5 QIS Centers
- Congrats to SQMS on the November 6th inauguration of The Quantum Garage at Fermilab, which hosts five

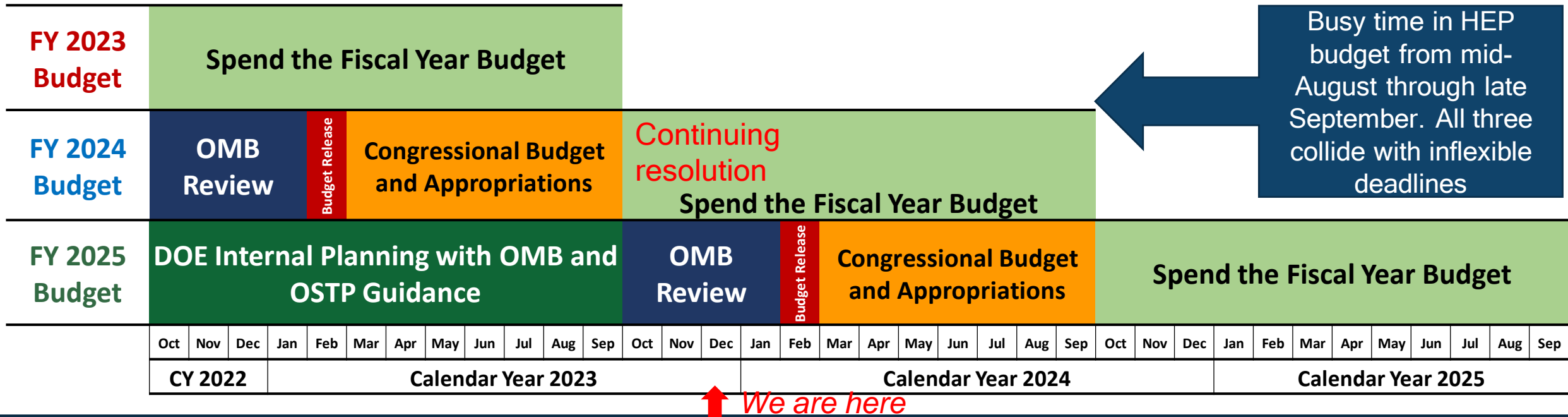
large dilution refrigerators



The Quantum Garage Inauguration: Ribbon-Cutting Ceremony
November 6, 2023, SQMS at Fermilab

The U.S. Federal Budget Cycle

- Typically, three budgets are being worked on at any given time
 - Executing current Fiscal Year (FY; October 1 - September 30).
 - Aggregating final FY 2023 End of Year requests to determine final distributions of reserves
 - OMB review and Congressional Appropriation for upcoming FY.
 - Preparing FY 2024 Initial Funding Plan for DOE Labs and Program Managers annual budgets assuming a 3-month CR
 - Agency internal planning for the second FY from now
 - Submitting the FY 2025 HEP narrative draft to SC budget and DOE CFO for review before it goes to OMB for review



U.S. Particle Physics Strategic Planning

Process

- Each of these processes provides important input to the 2023 P5 strategic process
 - Updated 2020 European Strategy for Particle Physics
 - NAS Astronomy and Astrophysics Decadal Survey (2021)
 - 2021-2022 Community Snowmass Process
 - New NAS Decadal Survey in Elementary Particle Physics
 - HEPAP Report on International Benchmarking
- DOE SC has just charged each FACA panel in the science programs to report on desired future facilities for next 10 years (More from Mike Procaro)
- We want to thank the P5 subcommittee for all of their hard work
- We look forward to the presentation this afternoon

