Experimental Landscape

Snowmass Community Summer Study

Seattle Snowmass Summer Meeting 2022

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I thank all my colleagues who kindly provided material for my presentation, especially the program managers at DOE and at NSF.

Outline

P5 will be charged to develop a strategic plan for U.S. particle physics for future. The starting point for the plan will be the present program.

Outline of my presentation:

- **General comments about the program**
- **Overview of experimental program, organized by P5 science driver**
- **Closing remarks**

In this presentation, I would like to convey the diversity, richness, and balance of the current experimental program.

- **Broad science scope, covering great range of different, but inter-related topics.**
- **Experiments with a diversity of scale, from small- to mega-**
- **Part of a global program of collaborative international efforts & shared facilities**
- **While P5 prioritizes projects, it does so in the context of the science drivers and of the program as a whole.**

Recall that P5 = Particle Physics Project Prioritization Panel.

Strategic vision of 2014 P5: Particle physics is global

The current U.S. HEP program is guided by the 10-year strategic plan of 2014 P5 report:

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

"Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community."

"The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere."

The U.S. experimental program depends upon reliable partnerships.

2014 P5's Science Drivers

2014 P5 distilled the compelling scientific questions developed by the 2012-2013 Snowmass community process into five topics that should drive the U.S. HEP program for the subsequent 10 years (within a 20-year vision):

- **Use the Higgs boson as a new tool for discovery.**
- **Pursue the physics associated with neutrino mass.**
- **Identify the new physics of dark matter.**
- **Understand cosmic acceleration: dark energy and inflation.**
- **Explore the unknown: new particles, interactions, and physical principles.**

P5 emphasized that the 5 science drivers are intertwined,
e.g. **synergy between precision physics and direct production,**
or the insights that cosmic surveys shed on neutrino properties.

P5 then identified the highest priority projects for a balanced program that addresses these science drivers in constrained budget scenarios.

Foundations of the experimental program

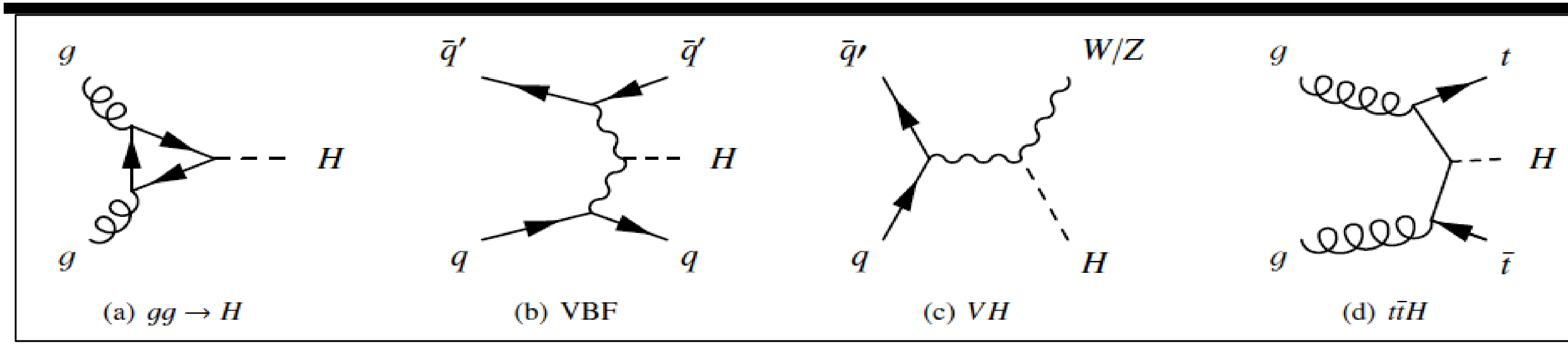
The experimental program is built upon the foundation of other critical research activities.

- Theory
- Technology R&D:
  - Accelerator R&D
    - See the 2015 HEPAP Accelerator R&D Subpanel report.
  - Detector R&D
    - See recent basic research needs (BRN) report.
    - including microelectronics
- Software & Computing
  - including AI/ML

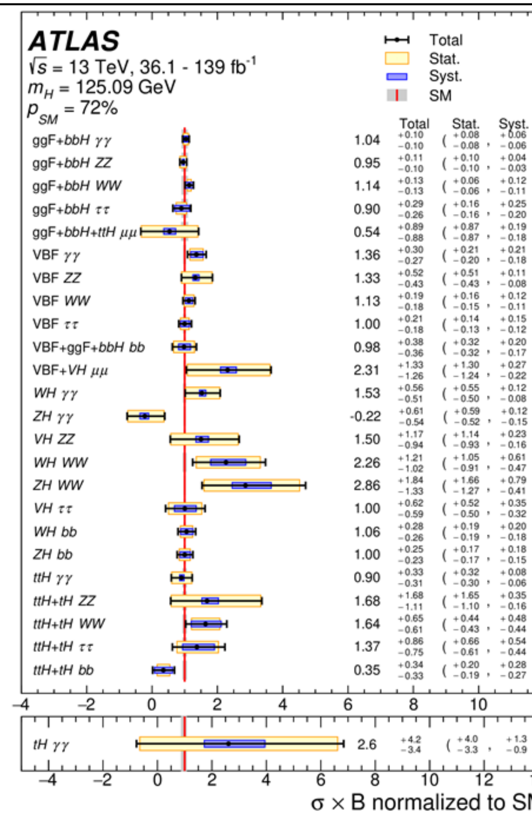
DOE & NSF support theoretical + experimental Quantum Information Science.

The experimental program, and its foundation, cannot exist without its expert science & technology workforce.

Use the Higgs boson as a new tool for discovery.



- **LHC and HL-LHC are the only means to produce and characterize the Higgs for the next decade or longer.**
  - **Precision measurements of Higgs properties leading to any deviations at the few %-level.**
  - **Access to rare processes, H decay to μμ.**
- **ILC, FCC-ee,** or other Higgs factory **would eventually allow measurements of higher precision.**
- **A very high energy proton-proton collider** (*e.g.* FCC-hh) **would later allow other improved measurements, particularly Higgs self-coupling.**



The U.S., the LHC, and the HL-LHC

LHC has been one of the largest investments of U.S. in HEP, ever.

- **LHC accelerator** (DOE)
- **ATLAS** (DOE+NSF), **CMS** (DOE+NSF), **LHCb** (NSF, DOE NP), **ALICE** (DOE NP)

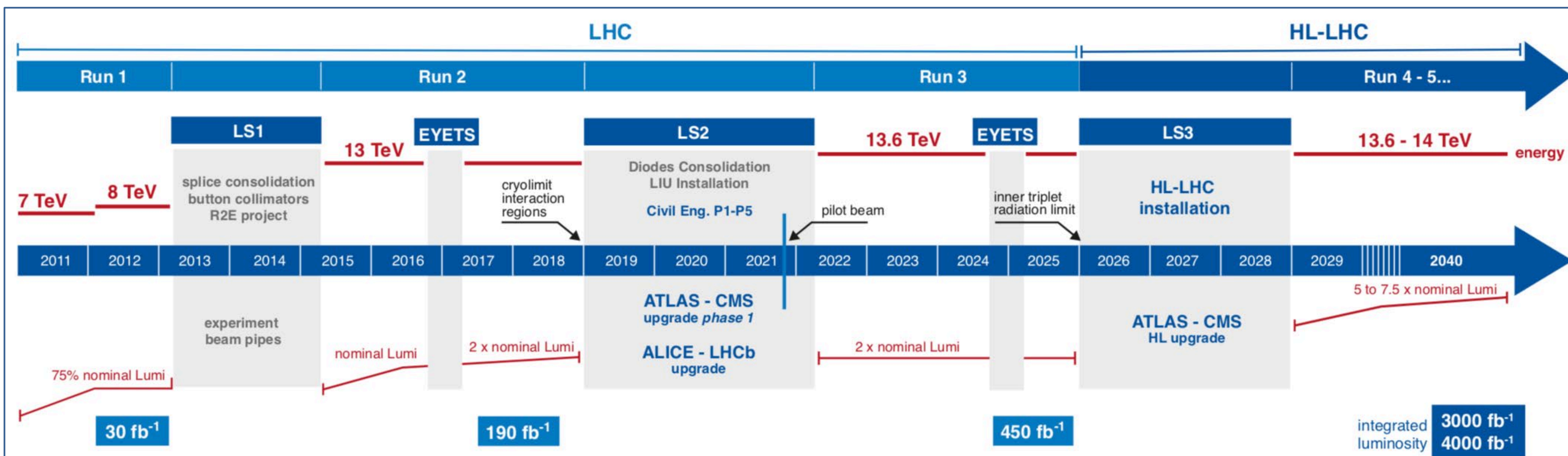
U.S. is single largest collaborating nation on both ATLAS & CMS.

- **US-ATLAS: ~19% of ATLAS; US-CMS: ~27% of CMS**

U.S. plays leading roles on LHCb (6 U.S. institutions)

U.S. LHC Detectors Operations Program – DOE + NSF

- **Supports Maintenance & Operations and Software & Computing**
- **Spearheads HL-LHC Software & Computing planning + R&D**



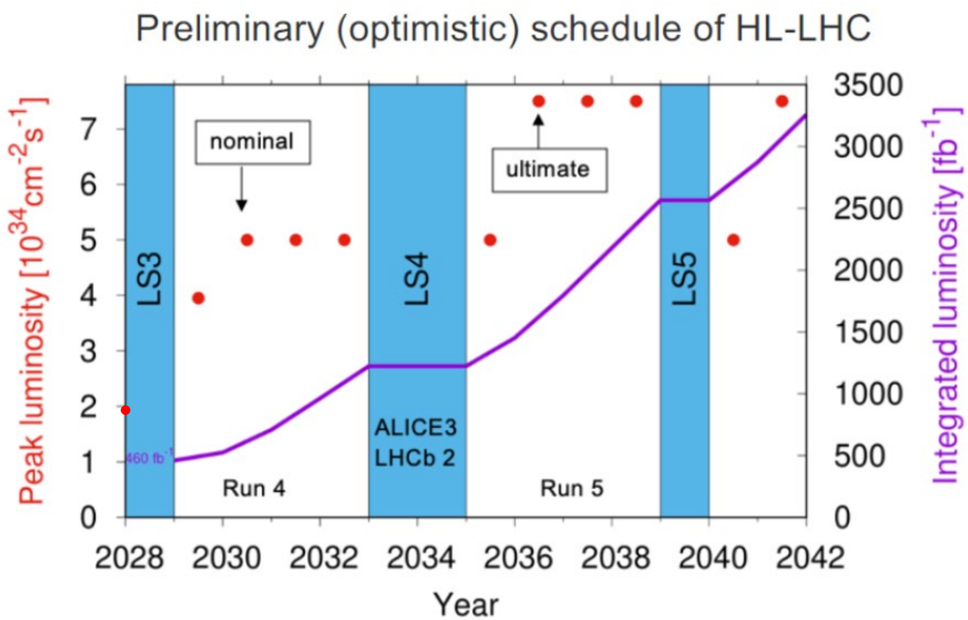
LHC and HL-LHC upgrades

"The LHC upgrades constitute our highest-priority near-term project."

Phase-I upgrades were installed during LS2 for Run 3 started July 5th.

U.S. investment continues for HL-LHC upgrades for Run 4.

- **DOE: HL-LHC AUP**
  - **Accelerator Upgrade Project**
  - CD-3 – December 2020;
    (re-baseline in 2022: COVID & LS3 sched)
- **DOE & NSF: HL-LHC [Phase-II] ATLAS & CMS upgrades**
  - NSF MRFEC: Feb 2020
  - CD-2's ATLAS + CMS in Fall 2022
  - Early start: CD-3's:
    - ATLAS – CD3a 9/21
    - CMS – CD-3a 6/21, CD-3b 6/22

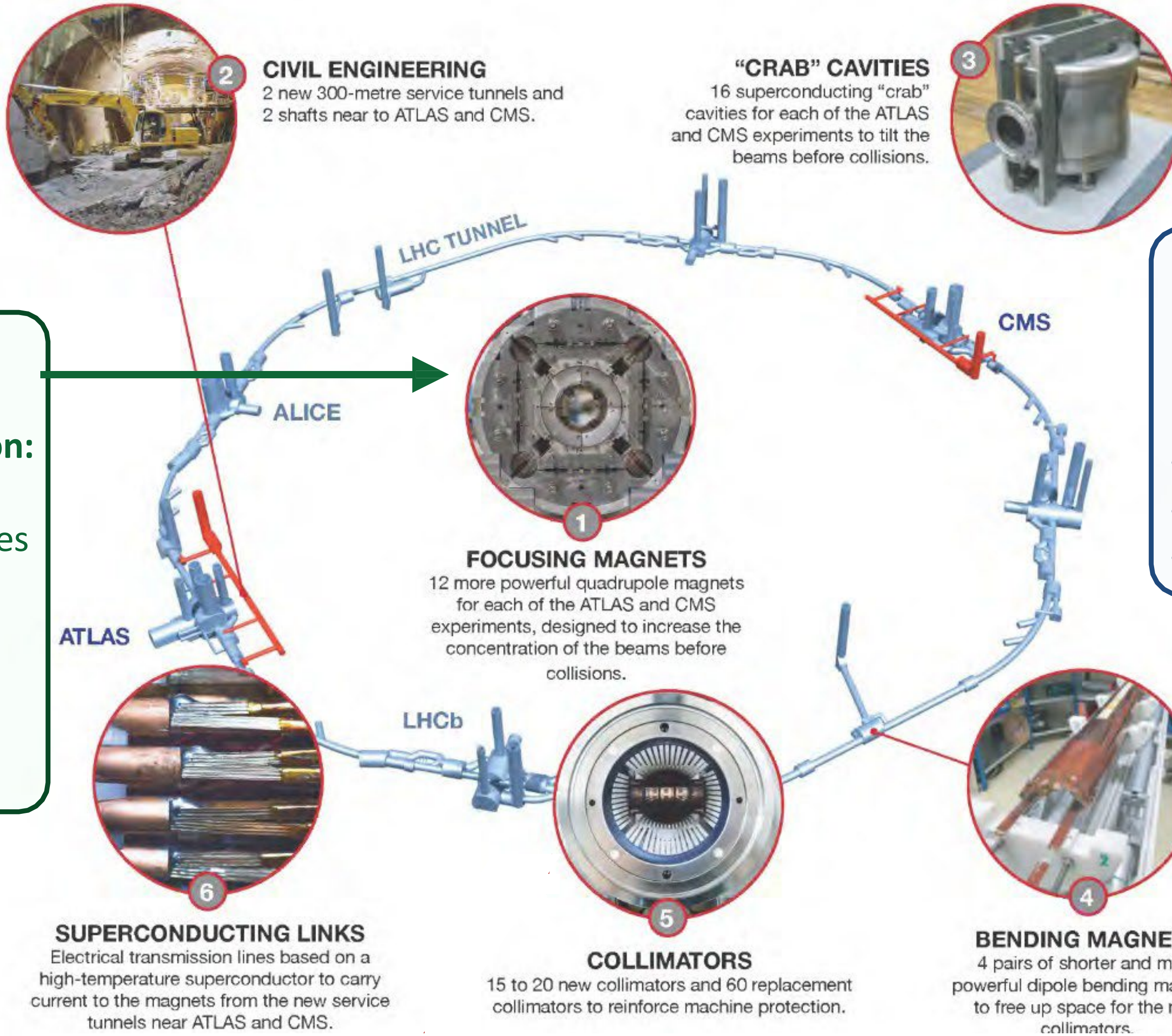


x 2.5, then *x 5* instantaneous luminosity
x 7 integrated luminosity (*wrt* end Run 3)

- **LHCb Upgrade I – installed in LS2**
- **LHCb Upgrade II – for LS4**
- **ESPPU highlighted flavor physics at LHC & HL-HLC.**

HL-LHC Accelerator Upgrade Project:
Enabling U.S. Science Participation at CERN's LHC

DOE contribution:
10 cold mass (Nb_3Sn) assemblies
- *4 each for ATLAS & CMS interaction regions*
- *2 spares*



DOE contribution:
RFD Crab Cavities
- *2 proto*
- *2 pre-series*
- *10 cavities*

CMS HL-LHC Upgrade

- **Upgrade for performance at high rate & high efficiency for LHC Run 4.**
- **NSF & DOE support large U.S. roles.** NSF MREFC – Feb. 2020; DOE CD-2 in Fall 2022

L1-Trigger/HLT/DAQ

DOE NSF

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

New Calorimeter Endcap

DOE

https://cds.cern.ch/record/2293646

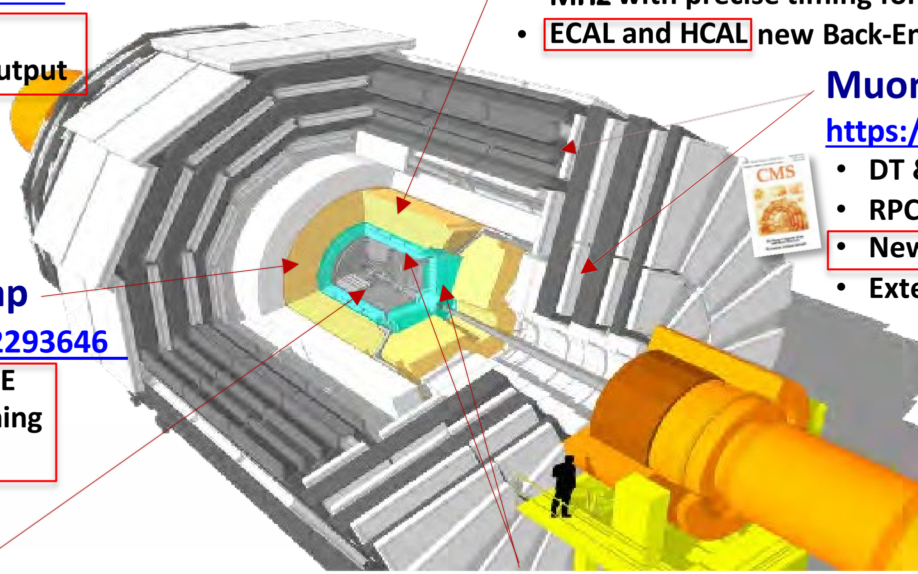
- Referred to as HGCAL, EC, CE
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Tracker

DOE NSF

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



Barrel Calorimeters

NSF

https://cds.cern.ch/record/2283187

- New FE/BE electronics for full granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems

NSF

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/2020886

All Funding Agencies

MIP Timing Detector

https://cds.cern.ch/record/2296612

Precision timing with:

DOE

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

ATLAS HL-LHC Upgrade

- **Upgrade for performance at high rate & high efficiency for LHC Run 4.**
- **NSF & DOE support large U.S. roles.** NSF MREFC – Feb. 2020; DOE CD-2 in Fall 2022

DOE Scope:

– Barrel Inner Tracker (pixel & strip detector)
– LAr Calorimeter front-end analog chip development
– DAQ hardware (data flow elements)
– Common systems and infrastructure projects

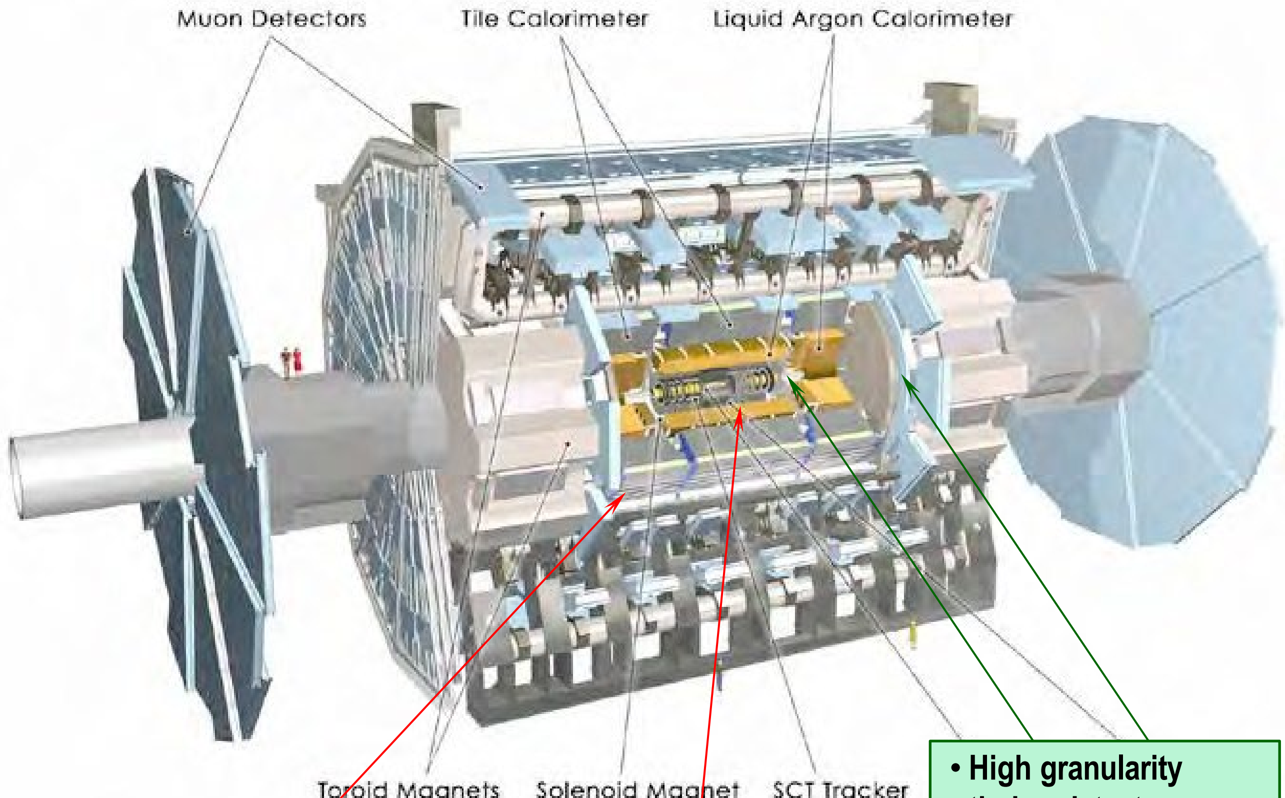
NSF Scope:

– 'Triggering' at high luminosities
– Readout electronics for LAr, Tile, Muons
– Common systems and infrastructure projects

Electronics Upgrade for LAr and Tile Calorimeters; muon system

Upgraded Trigger & DAQ: L0: 1 MHz; improved HLT

Infrastructure and Common Projects

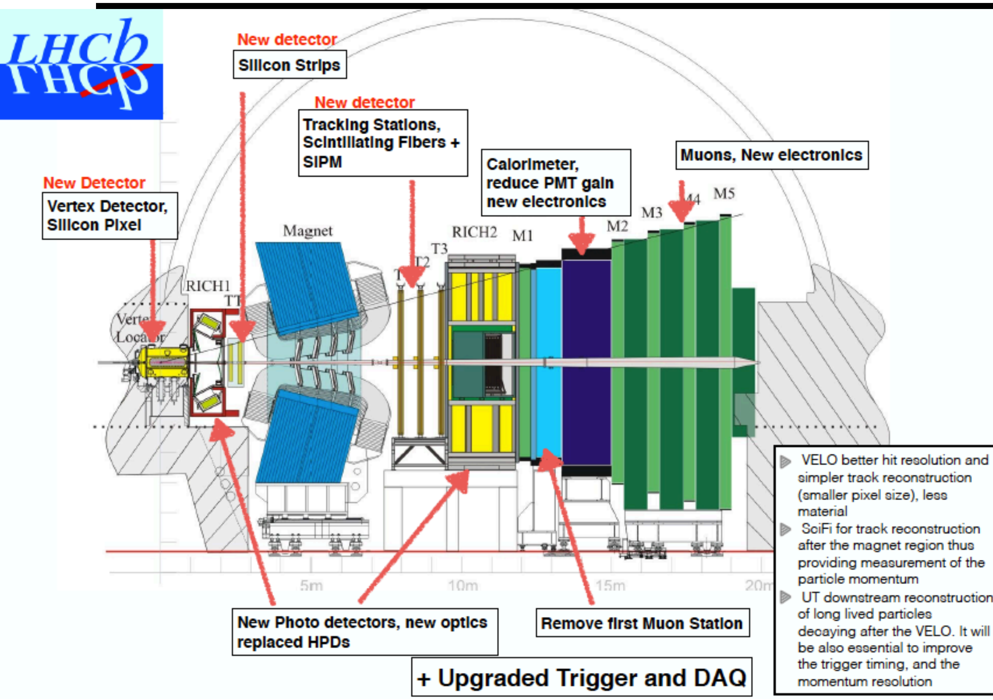


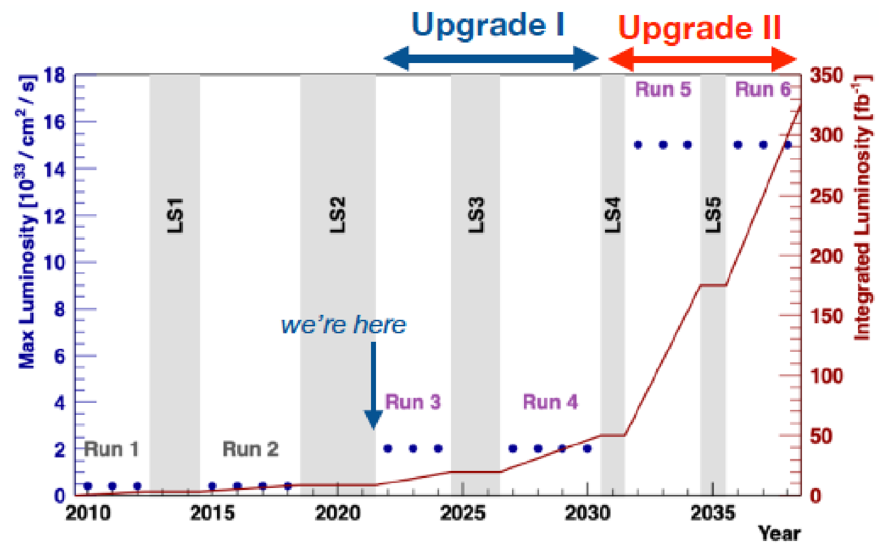
New muon chambers in the inner barrel region

New inner tracking detector (all silicon tracker, up to $|\eta|$=4)

- **High granularity timing detector (forward region)**
- **High-η muon tagger**

LHCb Upgrades I & II





Upgrade I

$\mathcal{L}_{peak} = 2.0 \times 10^{33} cm^{-2} s^{-1}$

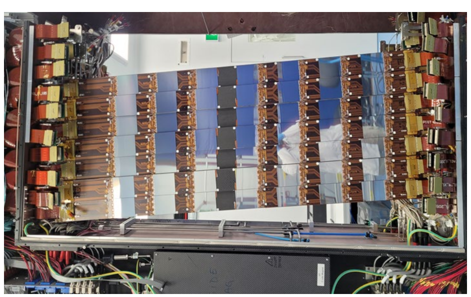
$\mathcal{L}_{int} = 50 fb^{-1}$

Upgrade II

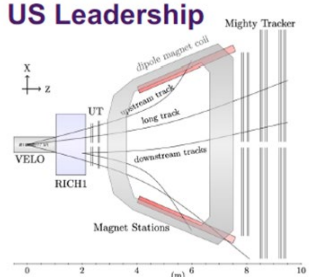
$\mathcal{L}_{peak} = 1.5 \times 10^{34} cm^{-2} s^{-1}$

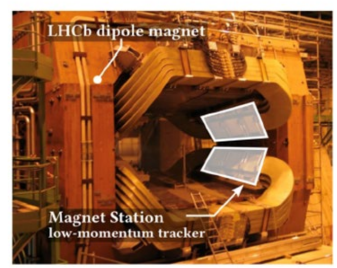
$\mathcal{L}_{int} = 300 fb^{-1}$

U.S. contributions:
- GPU trigger application
- Triggers for inclusive heavy flavor & dark sector



US Leadership



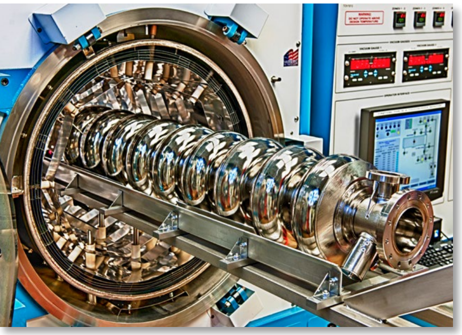


Upgrade Ib:
U.S. leadership in low-momentum tracker stations in magnet

U.S. leadership in upstream tracker detector

Upgrade II – *Key features*
- 4D vertex detector
- 5D calorimeter - *U.S. R&D*

Seeding the future: Energy Frontier planning



Future collider strategy in the 2014 P5 plan:

- **Support development & realization of ILC**
  - Focus on SRF R&D, high gradient & high Q
- **R&D towards a very high-energy pp collider**
  - Focus on next-generation high-field dipoles through U.S. Magnet Development Program.

Advancing colliders of the proposed size, scale & complexity requires intergovernmental discussion & global coordination.

- Concerted U.S. Govt. interagency effort during the last ~5-6 years to support moving forwards with a proposed ILC in Japan and to collaborate with CERN on a proposed FCC.

DOE coordinates with ILC International Development Team to prepare ILC for its "Pre-Lab" phase.

- DOE plans to participate in any future intergovernmental discussion with Japan & global partners.

2020: DOE & CERN signed a FCC agreement to continue R&D & participate in the FCC Feasibility Study

Current efforts for ILC and/or FCC focus primarily on accelerator R&D, but DOE grants for the LHC experiments may apply up to 25% funds for development and physics studies for experiments for future colliders.

Other collider concepts are being considered during Snowmass/P5 process, which will guide future U.S. R&D and investments

Pursue the physics associated with neutrino mass.

"In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab."

U.S. working abroad:

Long-baseline:
- T2K

Atmospheric/solar:
- SuperK

Reactor:
- Daya Bay
- JUNO

Short-baseline:
- IsoDar

Currently at FNAL:

Short-baseline:
- MINERvA
- MicroBooNE*
- ICARUS

Long-baseline:
- NOvA

→

Future Outlook at FNAL:

Short-baseline:
- SBN
  - SBND
  - ICARUS

Long-baseline:
- LBNF/DUNE

Others in U.S.:

Short-baseline:
- **COHERENT** (ORNL)
- **ANNIE** (R&D; FNAL)
- **CCM** (LANL)

Reactor:
- **PROSPECT*** (ORNL)

Atmospheric:
IceCube

$0\nu2\beta$:
EXO-200
($0\nu2\beta$ is now DOE NP)

Neutrino mass:
Project-8

Cosmic surveys also shed light on neutrino properties.

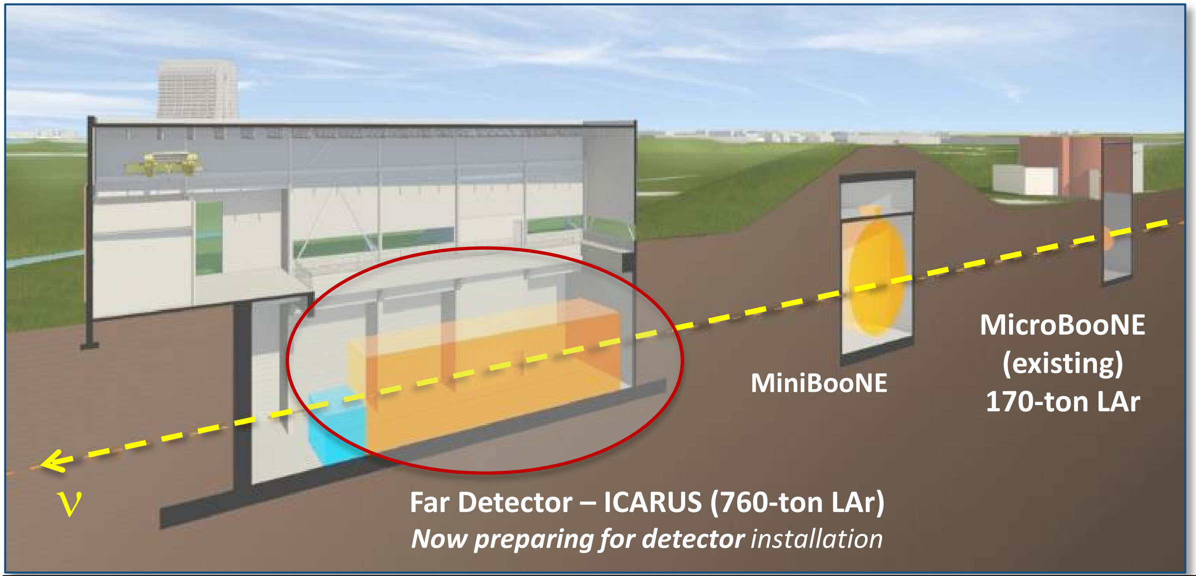
Short-Baseline Neutrino Program

Two principal goals:

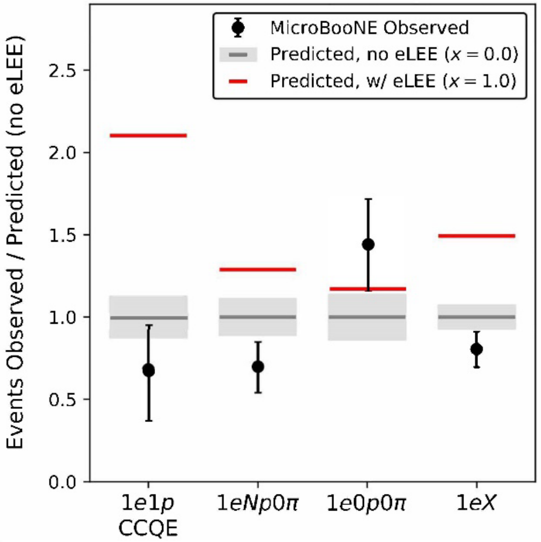
- **Resolve experimental anomalies in measured ν-spectrum, including search for sterile neutrinos.**
- **Demonstrate the liquid argon TPC detector technology for DUNE.**

Three detectors:

- **MicroBooNE -** ***physics running complete; first results published on ½ data set; 47 papers, ½ physics + ½ R&D***
- **ICARUS – brought from Gran Sasso, Italy via refurbishment at CERN –** ***operating***
- **SBND – Short-Baseline Near Detector –** ***under construction***

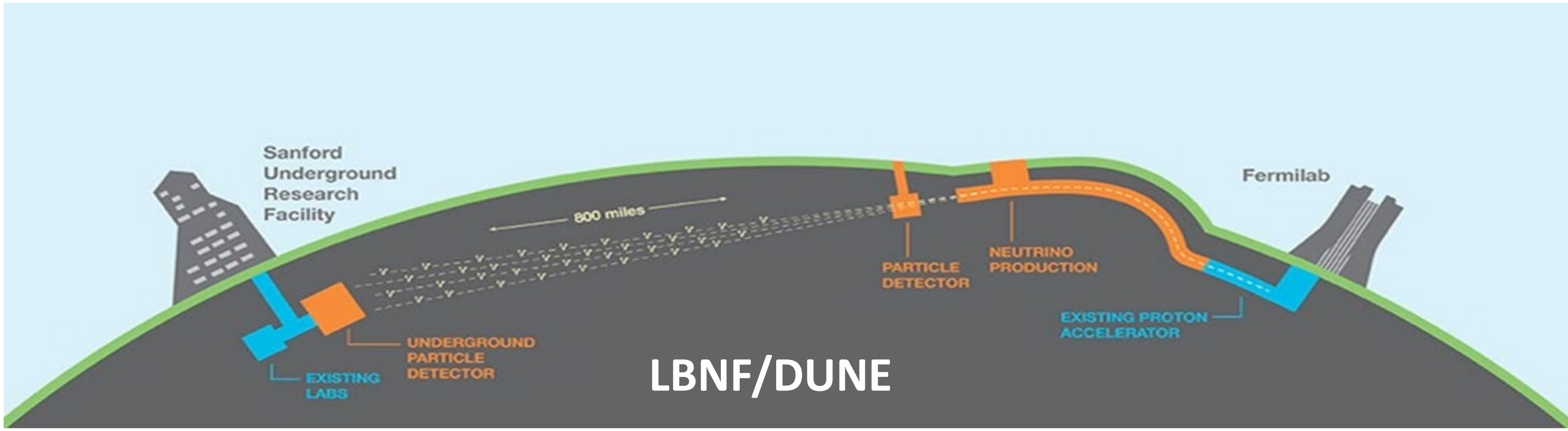


MicroBooNE ν_e appearance



Long-Baseline Neutrino Program – LBNF/DUNE

Long-Baseline Neutrino Facility / Deep Underground Neutrino Expt.



- **Identified by P5 as the highest priority large project in its time frame.**
- **Centerpiece of a U.S.-hosted, international neutrino program.**
- **The 1st international science facility hosted in the U.S.**

>1100 collab.
198 inst.
32 nations

UK-U.S. S&T Agreement
20 Sept 2017

Strong support for international collaboration within U.S. Govt.

US DOE – India DAE S&T Agreement for neutrino physics - 16 April 2018

Proton Improvement Plan II (PIP-II)

1.2 MW proton beam on target; beam ready when LBNF ready (2031); upgradeable

Will also support other research goals by providing increased beam power and high reliability to future Fermilab experiments.

Replace existing 50-year-old linac with a high-power, 800-MeV SRF linac.

Based on LCLS-II experience (and ILC R&D)

Being built with international partners: India, Italy, UK, France, Poland.

CD-3 - April 2022 (CD-3a – March 2021)

Ultimate goal for upgrade of proton complex is >2 MW to LBNF w/ Booster upgrade.

Identify the new physics of dark matter.

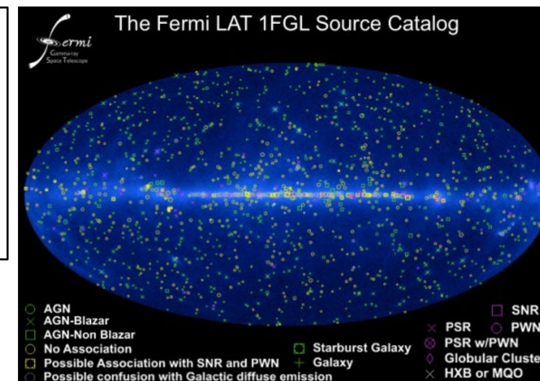
P5: "It is imperative to search for dark matter along every feasible avenue."

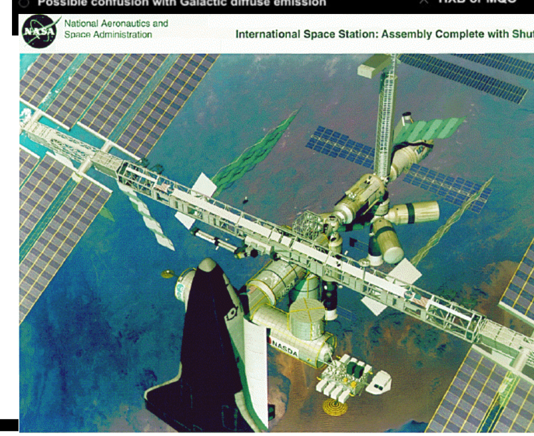
4 complementary experimental approaches, each providing essential clues:

- **direct detection,**
- **indirect detection,**
- **observation of large-scale astrophysical effects,**
- **dark matter production at accelerators.**

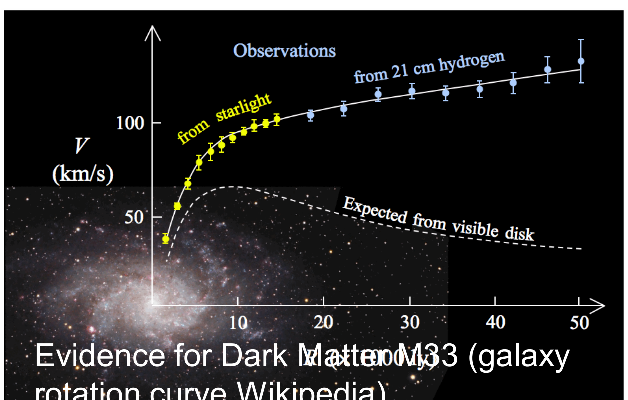
Indirect detection:

- **Research continuing with Fermi-LAT & AMS-02.**
- **HAWC sensitive to very heavy DM particles.**
- **DOE has no new initiatives planned.**





Large-scale astrophysical effects:



Evidence for Dark Matter M33 (galaxy rotation curve Wikipedia)

Direct detection searches for dark matter

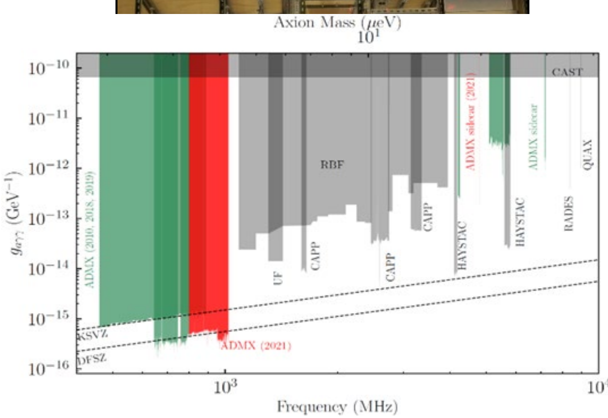
DM-G2 program: 3 complementary experiments

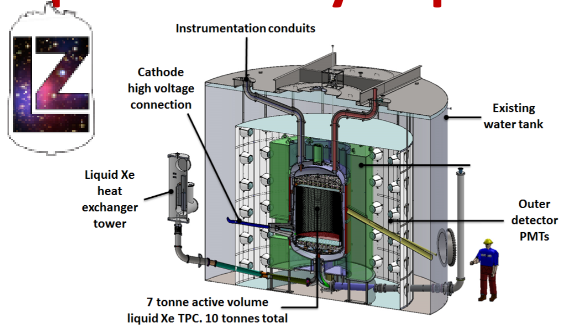
ADMX
AXION DARK MATTER EXPERIMENT

at Univ. of Washington

Axion search

Operating since 2017

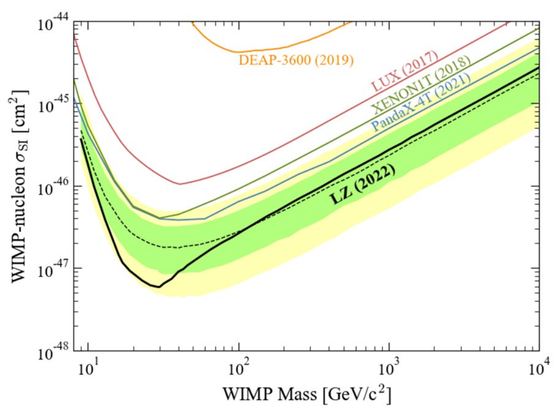




at SURF (South Dakota)

WIMP search
LXe

First results this year

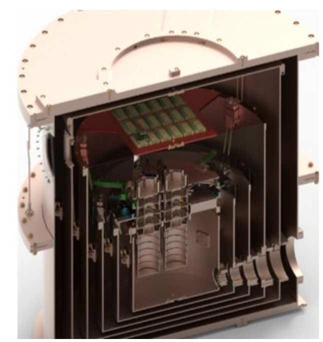


SUPER CDMS
Cryogenic Dark Matter Search

DOE + NSF-PHY partnership

WIMP search
Si/Ge at SNOLab

Fabrication complete - 2022
Operations – 2024



NSF supports numerous searches:
ABRACADABRA, ALPS-II, ARIADNE, COSINE, DAMIC-M, DarkSide, HAYSTAC, SABRE, SENSEI, XENONnT, R&D

Looking further forward, 2014 P5 also recommended one or more DM-G3 experiments.

Dark matter production at accelerators

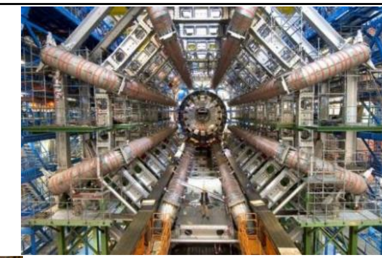
Dark matter production with particle colliders

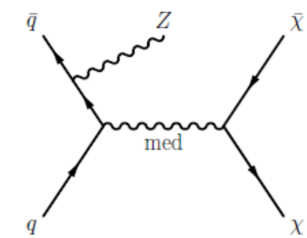
Many DM searches at the LHC in ATLAS + CMS + LHCb & FASER

- **“invisible signatures”** (mono-X; h->invisible, etc.)
- **“visible signatures”** (e.g. mediator to dijets)
- **searches in the SUSY context**

This active program will continue at HL-LHC.

Results also from *BABAR*, BELLE & BELLE-II.



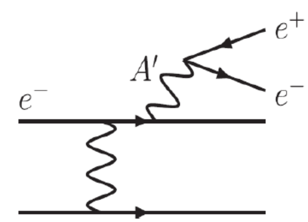


Dark matter production in intense particle beams

JLab: Heavy Photon Search (HPS); APEX in electron/positron beam

LANL: Coherent CAPTAIN-Mills (CCM10) in neutron beam

New concepts under study in context of DMNI: e.g. CCM200, LDMX



Dark matter future planning via:

All experimental techniques were explored at workshop on Dark Matter in 2017.

U.S. Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

Dark Matter New Initiatives funds development of 6 small project concepts

4 in Cosmic Frontier, 2 in Intensity Frontier

Understand cosmic acceleration: dark energy & inflation

Dark energy: complementary imaging & spectroscopic surveys

Transitioning from Stage III:

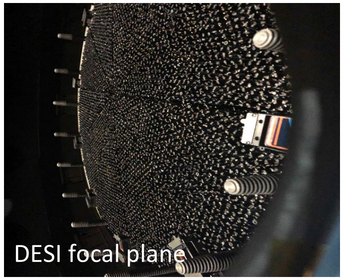
- **eBOSS – Extended Baryon Oscillation Spectroscopic Survey – final results 2020**
- **DES – Dark Energy Survey – survey complete; data processing nearing completion**

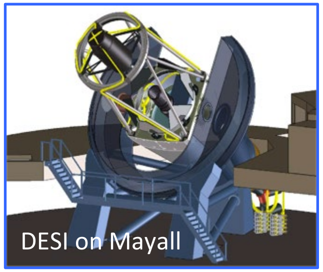
to Stage IV:

DESI

Dark Energy Spectroscopic Instrument

Data taking started 2021
Fire has interrupted


DESI focal plane


DESI on Mayall

Vera C Rubin Observatory

Legacy Survey of Space and Time (LSST)

aka Large Synoptic Survey Telescope

LSSTcam completed in 2021; to Chile in 2023
DOE + NSF MREFC
Dark Energy Science Collaboration (DESC) planning
Data taking to start late 2024.


Rubin telescope – NSF-AST


LSSTCam focal plane - DOE

Understand cosmic acceleration: dark energy & inflation

Inflation: Cosmic Microwave Background (CMB)

SPT-3G

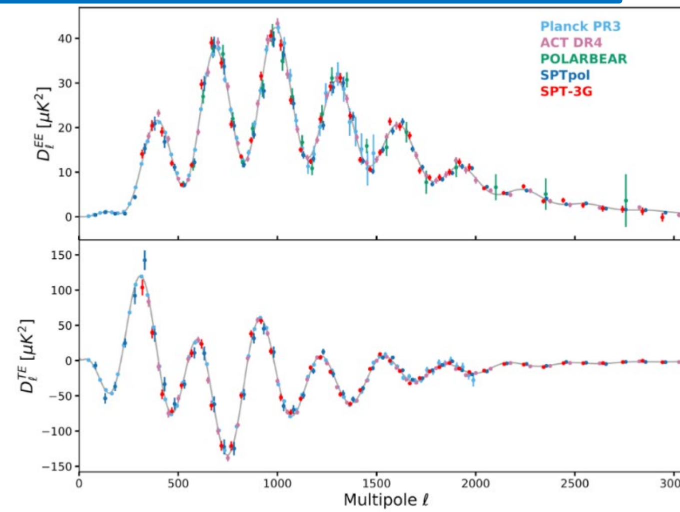
Operating Stage 3:

South Pole Telescope

Survey started in 2018

DOE-NSF partnership

1st science results - 2021



Planning for next generation:

CMB Stage 4 (CMB-S4)

Recommended by 2014 P5 + ASTRO2020; DOE-NSF partnership

CMB-S4 **Concept Definition Taskforce Report** approved in 2017; CD-0 - 2019

science goals, technical requirements, strawman concept

Learned in 2022 that must reduce footprint to fit South Pole infrastructure.

A note: P5 suggested international collaboration and coordination on Stage 4.

Dark Ages initiative (w/NASA): **LuSEE-Night** – Pathfinder mission to search for Dark Ages signal on lunar farside; MIE started FY22; launch 2025.

Measure low-frequency radio sky; sensitive to 21-cm emission from hydrogen at high redshift (*z>30*)

Explore the unknown.

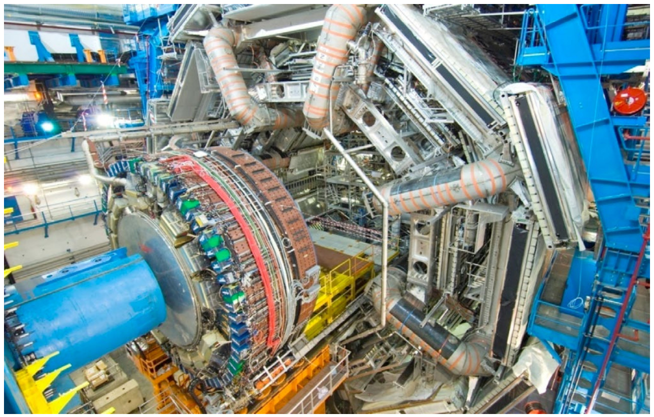
Explore the unknown: new particles, interactions, and physical principles.

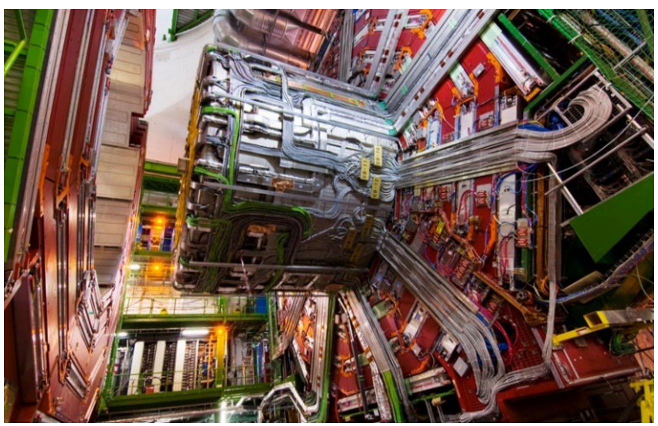
Some approaches to exploring the unknown as outlined by P5:

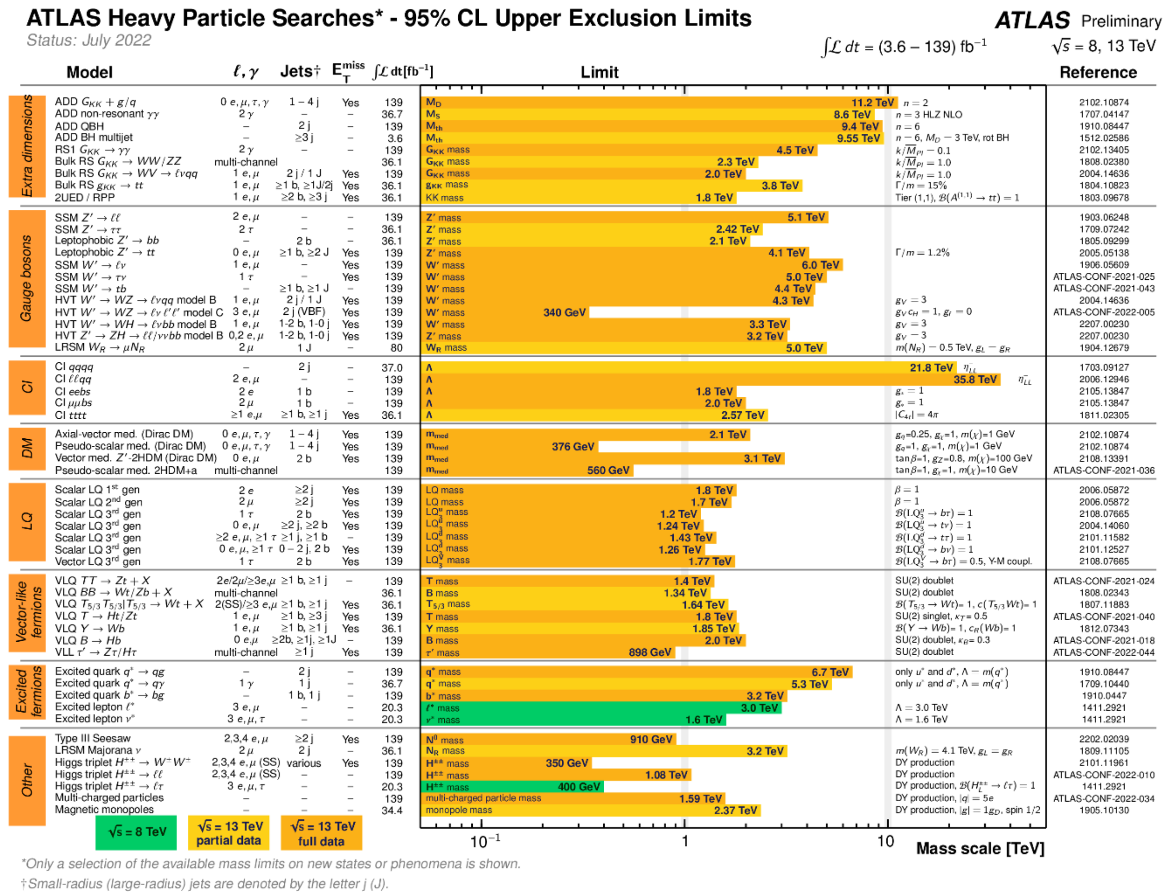
- *High energy colliders – ATLAS + CMS*
- *Precision physics & rare processes*
  - *Heavy quarks & tau leptons – LHCb, Belle-II*
  - *Rare kaon decays – KOTO, NA62*
  - *Rare muon decays and processes – Mu2e, MuonE,*
  - *Muon magnetic moment – Muon g-2*
  - *Baryon number violation – LHCb*
  - *Electric dipole moments - ACME*
  - *CPT* - CeNTREX*
  - *Monopoles* - MoEDAL*
- *Cosmic particles – AMS-02, HAWC, Pierre Auger, VERITAS, BEACON, pSCT, ARA, IceCube, Radar Echo Telescope, RNO-G, SNEWS (synergy w/ multi-messenger astro)*
- *New low-mass particles (e.g. hadron spectroscopy) – LHCb*

Explore the unknown at high-energy colliders

Searches at high-energy colliders are one approach to exploring the unknown.





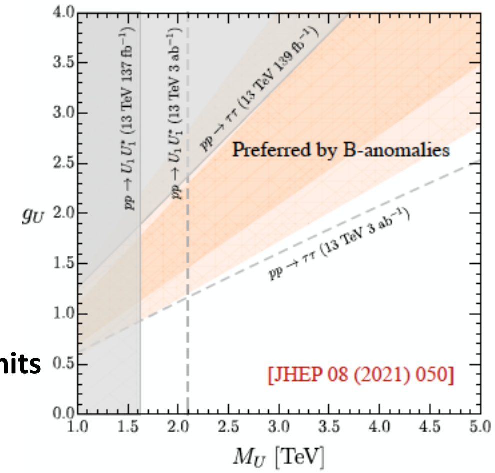


HL-LHC => Up to 40% larger discovery potential for new physics than prior to upgrades

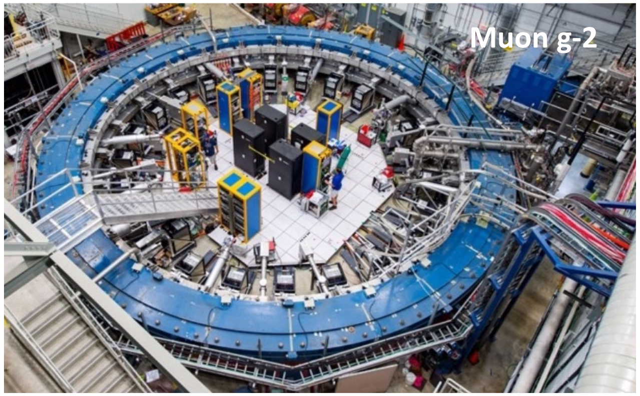
Explore the "unknown" thru precision measurements

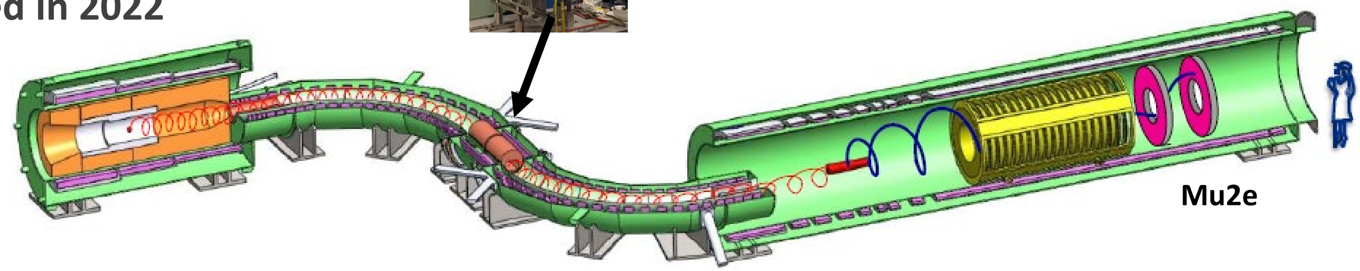
- ***Ongoing precision experiments:***
  - Collaboration with Japan on *K* meson studies with K0T0 and on heavy quark and τ lepton precision studies with Belle II.
  - LHCb at LHC
    - Highlights in semi-leptonic *B* decays, hadronic *B* decays, CKM matix, charm mixing & CPV

LHC leptoquark limits & B anomalies



- **The FNAL Muon Program**
  - **Muon g-2**
    - Results from 1st year running published
    - Now has 19x data of BNL predecessor from 5 years under analysis
  - **Mu2e**
    - Under construction (CD-3 – 2016)
    - Re-baseline planned in 2022
    - 1st run in 2026





DOE HEP MIE Project Status

COVID seriously impacted numerous projects.

Subprogram		TPC ($M)	CD Status	CD Date
INTENSITY FRONTIER				
LBNF/DUNE		~3000	CD-3a	Sept 1, 2016 (CD-1RR in July 2022)
Proton Improvement Project (PIP-II)		978	CD-3	April 18, 2022
Muon-to-Electron Conversion Experiment (Mu2e)		273.7	CD-3	July 14, 2016 (Rebaseline expected in 2022)
ENERGY FRONTIER				
LHC ATLAS Detector Upgrade		33.25	CD-4	Aug 19, 2019
LHC CMS Detector Upgrade		32.22	CD-4	June 10, 2019
High-Luminosity LHC (HL-LHC) Accelerator Upgrade		242.72	CD-3	Dec 21, 2020 (Rebaseline expected in 2022)
High-Luminosity LHC (HL-LHC) ATLAS Detector Upgrade	+ NSF MREFC	149-181	CD-3a	October 16, 2019 (CD-2 in Fall 2022)
High-Luminosity LHC (HL-LHC) CMS Detector Upgrade	+ NSF MREFC	144-183	CD-3b	June 24, 2022 (CD-2 in Fall 2022)
COSMIC FRONTIER				
Cosmic Microwave Background, Stage 4 – CMB-S4		320-395	CD-0	July 25, 2019
LUX-ZEPLIN (LZ)		55.5	CD-4	September 21, 2020
Super Cryogenic Dark Matter Search - SNOLAB (SuperCDMS-SNOLAB)		40.3	CD-3	November 18, 2021
Dark Energy Spectroscopic Instrument (DESI)		56.33	CD-4	May 11, 2020
Large Synoptic Survey Telescope Camera (LSSTcam)	+ NSF MREFC	168	CD-4	September 28, 2021
ADVANCED TECHNOLOGY R&D				
Facility for Advanced Accelerator Experimental Tests II (FACET-II)		26	CD-4	September 13, 2021

Closing remarks

The U.S. experimental particle physics program has been guided for the last several years by the strategic plan presented in the 2014 P5 report. It is time for an update.

The 2014 P5 plan is motivated by intertwined 5 science drivers:

- **Use the Higgs boson as a new tool for discovery.**
- **Pursue the physics associated with neutrino mass.**
- **Identify the new physics of dark matter.**
- **Understand cosmic acceleration: dark energy and inflation.**
- **Explore the unknown: new particles, interactions, and physical principles.**

The 2014 P5 strategic plan is:

- science driven.
- broad, covering a great range of different, but inter-related questions.
- a balanced program (not a strict prioritization).
- part of a global program of international collaborations & shared facilities.

The 2023 P5 strategic plan will build upon today's experimental program and upon the projects that will soon complete. This Snowmass Community Summer Study will provide the new information upon which the 2023 P5 strategic plan will be built.

=> Let's assemble a plan that shares the strong characteristics of the 2014 plan.

Thank you.