Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Science Progress since 2010

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Fermilab Deputy Director for Research
27 July 2022

NATIONAL ACADEMIES Sciences Engineering Medicine

Elementary Particle Physics: Progress and Promise

Outline

- What is elementary particle physics
- Discoveries in particle physics since 2010
- Consensus view of the road ahead
- Technology advances in particle physics since 2010
- Evolution of the HEP program since 2010
- Possible discovery menu in the coming decade from the current program
- Bottom line

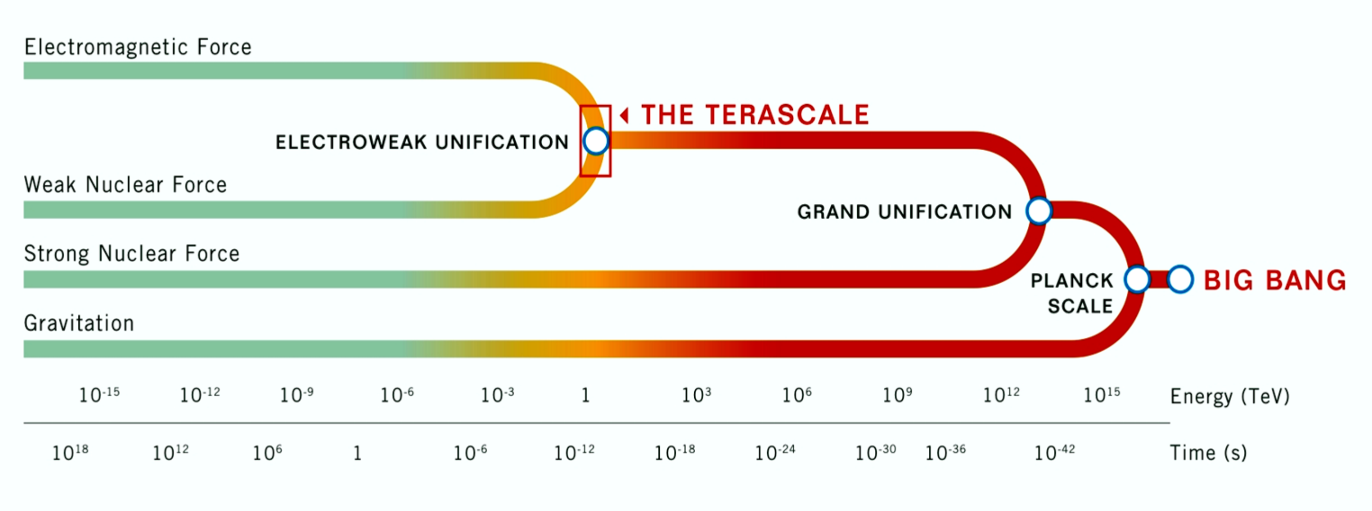
What is elementary particle physics (scientific definition)

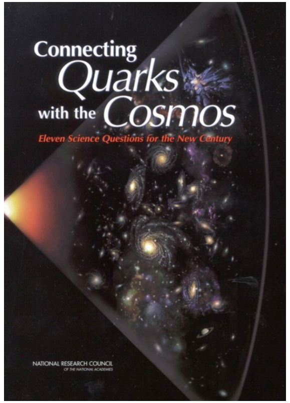
Particle physics has the ambitious goals of uncovering the most fundamental constituents of reality, *whatever they are*, and deciphering the rules by which those constituents interact.

- Depending on context, physical processes may be described in terms of constituents that are particles, waves, fields, strings, quantum information, …

What is elementary particle physics (scientific definition)

- Particle physics is often called High Energy Physics to emphasize the physical regime that we are (usually) exploring, rather than the constituents
- Particle physics has a natural overlap with Cosmology, which is trying to understand the earliest history of the universe, *whatever it was like*





What is elementary particle physics (programmatic definition)

HEP is whatever DOE HEP funds

EPP is whatever NSF EPP funds

These programmatic boundaries are not always scientifically justifiable:

- Neutrinoless double beta decay is not HEP in the U.S. but is in Europe
- Gravity waves are NSF but not HEP

But programmatic boundaries can also change over time:

< 2013 Cosmic Microwave Background was NSF but not HEP
2014 P5 endorses CMB-S4 as joint DOE-NSF project

< 2018 QIS was NSF and NIST but not DOE Office of Science
2022 DOE SC funding quantum science at approx. $200M/year

What is elementary particle physics (defined by the big questions)

- Why Electroweak Symmetry Breaking
- What is the history of the Electroweak Phase Transition
- The reason for the hierarchy in Fermion Masses and their flavor structure
- The identity of Dark Matter
- The origin of the Matter-Antimatter Asymmetry
- The generation of Neutrino Masses
- The cause of the Universe's accelerated expansion - Dark Energy
- What are the quantum properties of Gravity
- What caused Cosmic Inflation after the Big Bang

Discoveries in particle physics since 2010

Discoveries: Large Hadron Collider

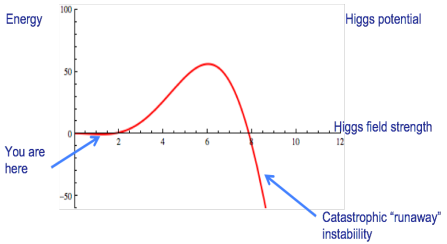
What happened

2012: discovery of the Higgs boson by ATLAS (4 U.S. labs) and CMS (Fermilab) at the CERN LHC

Significance

There was a phase transition in the early universe where the Higgs field turned itself on and broke electroweak symmetry

The measured Higgs boson mass, 125 GeV/c^2, implies in the SM that the vacuum is only metastable



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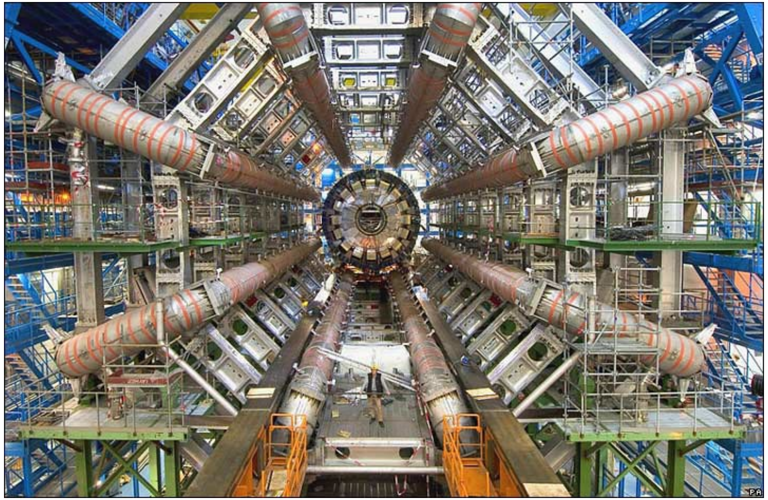
Discoveries: Large Hadron Collider

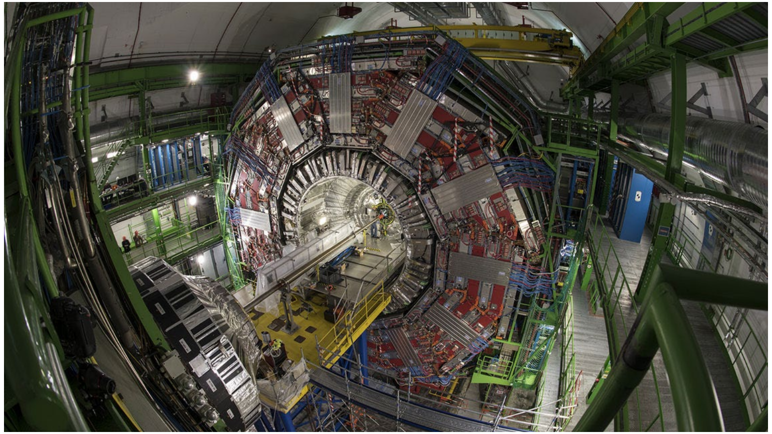


What happened

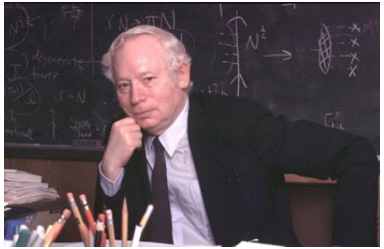
2017: First observation ATLAS and CMS that Higgs bosons decay to pairs of tau leptons

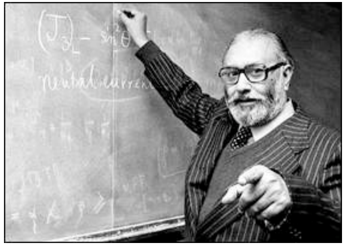
2018: First observation ATLAS and CMS of the dominant decay mode of the Higgs boson to pairs of b quarks, and of ttH production

Significance



The same field that breaks electroweak symmetry also gives mass to (at least some) matter particles, and the Higgs couples more strongly to heavier matter particles





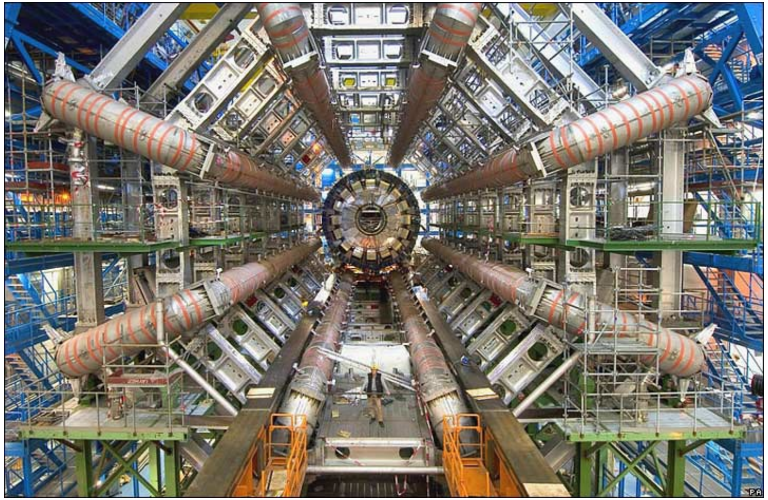
Discoveries: Large Hadron Collider

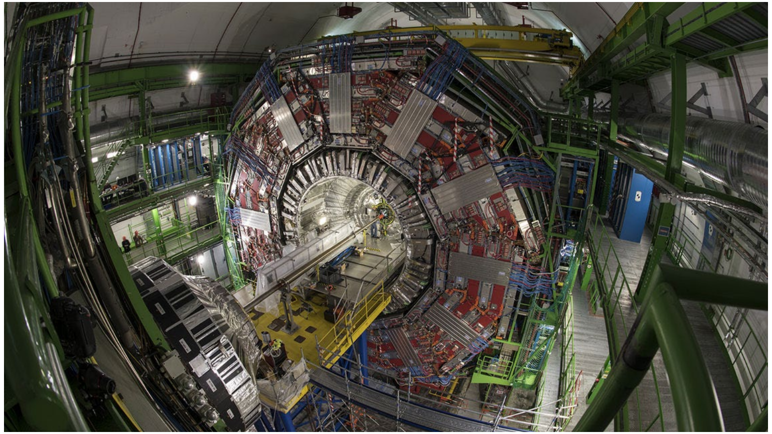
What happened

2020: the CMS experiment (CERN,Fermilab) announces the first observation of Higgs boson decays to muons

Significance

The SM predicts that the same Higgs field gives mass to all three generations of matter particles; before 2020, we only knew that the Higgs field coupled to the third generation (t, b, tau)





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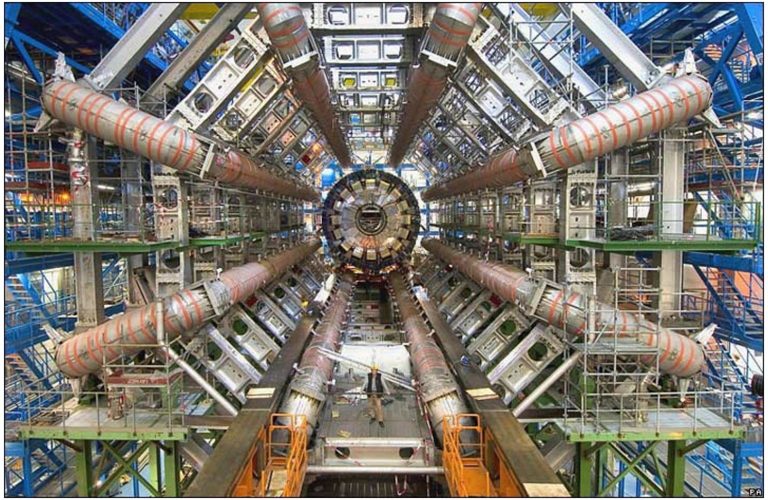
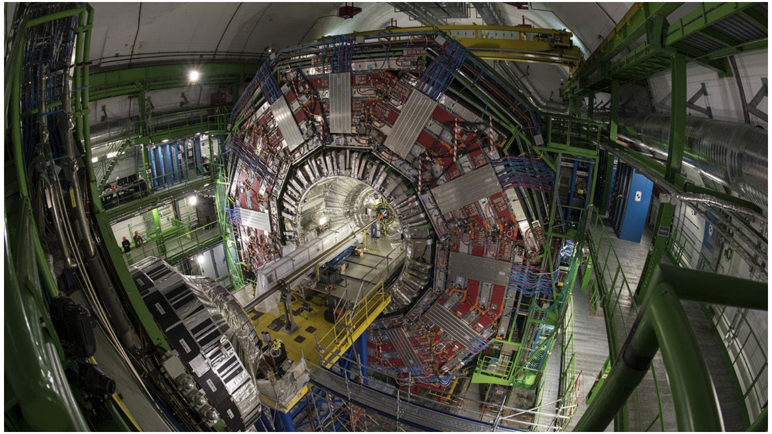
Discoveries: Large Hadron Collider



What happened

2014-2020: ATLAS and CMS show that the Higgs total width is no more than 2-3 times the SM value, and Higgs bosons decay to invisibles no more than 10% of the time



Significance

Direct constraints on the Higgs boson decaying to exotic particles outside the SM, like dark matter or dark sector portals

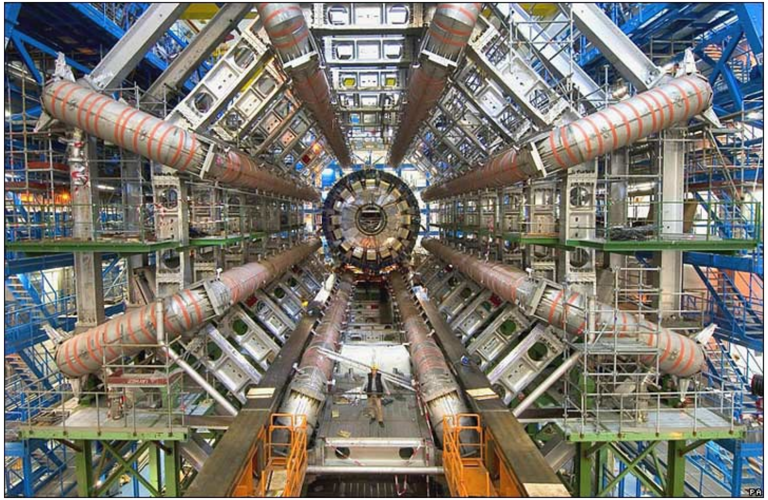
Discoveries: Large Hadron Collider

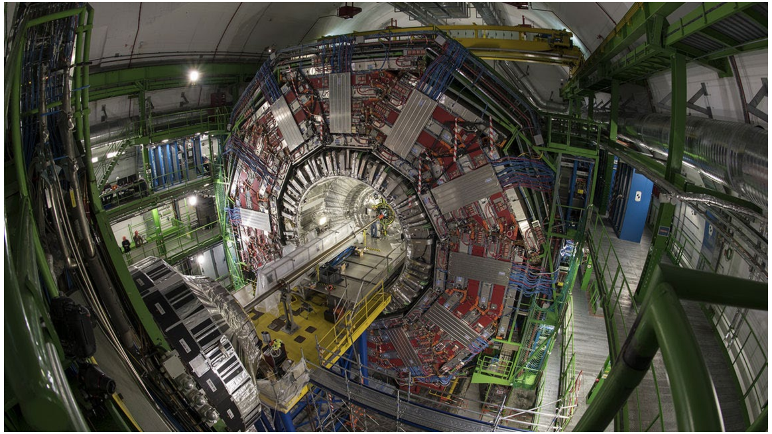
What happened

2022: ATLAS and CMS show that the self-coupling of the Higgs is no more than ~10 times the SM value

Significance

First direct constraints on the shape of the Higgs potential responsible for the electroweak symmetry breaking phase transition in the early universe





Discoveries: Neutrinos

What happened

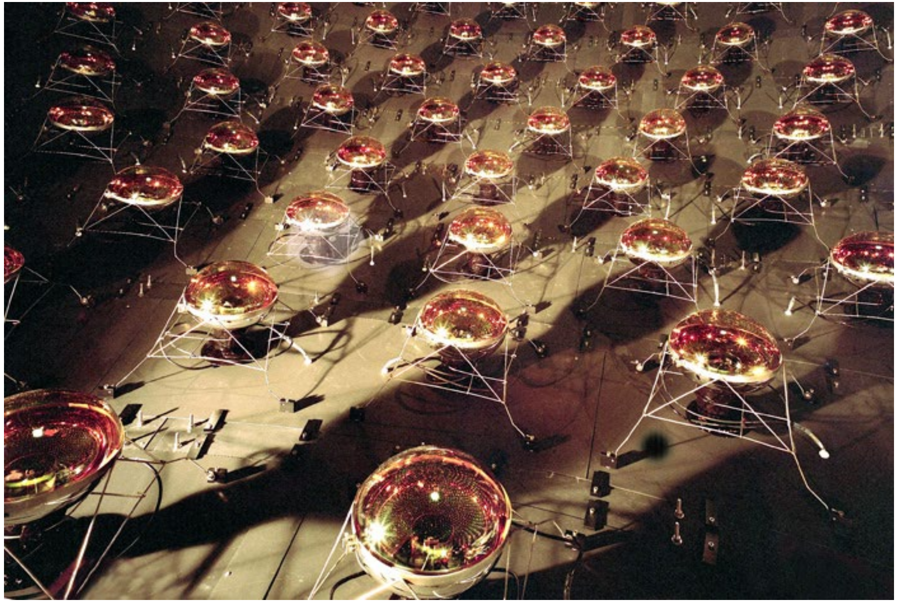
2012: first measurement of the neutrino mixing angle θ_{13} by the Daya Bay experiment, a collaboration of the U.S. (LBNL) and China

Significance

The large value of θ_{13} implies that an experiment like DUNE can observe CP violation (if it exists) in long baseline neutrino oscillations

Rapid pivot by the U.S. HEP program

Discoveries: Neutrinos



What happened

2013: the Fermilab MiniBooNE experiment reports an unexplained excess of low energy electron neutrino candidate events

Significance

After five additional years of data taking and analysis, a 4.8 sigma excess remained; could be a signal of sterile neutrinos or other new phenomena

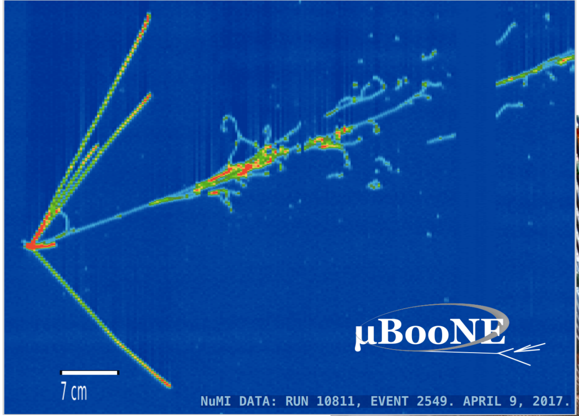
Discoveries: Neutrinos

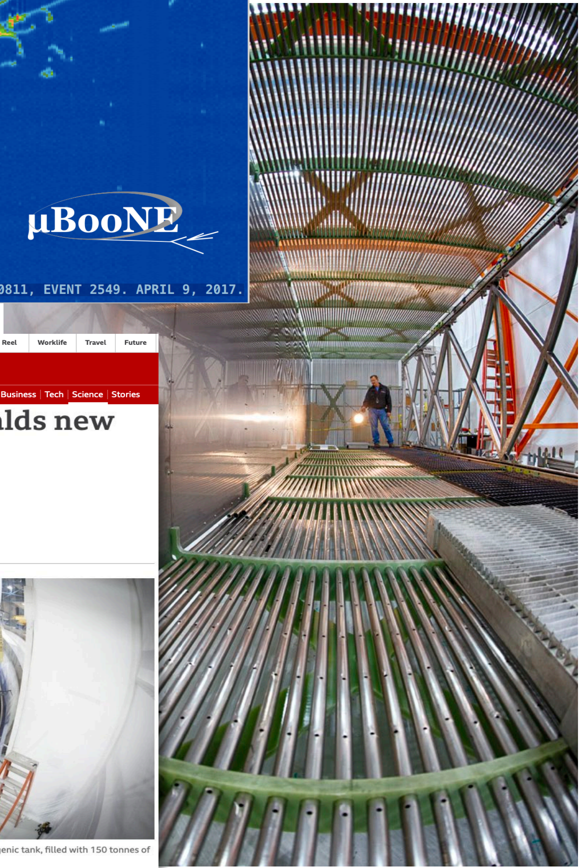
What happened

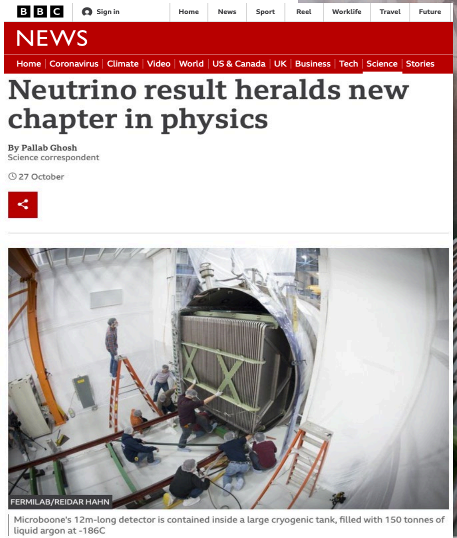
2021: the Fermilab MicroBooNE experiment rules out the simplest explanations of the MiniBooNE excess

Significance

- Demonstrated the impressive capabilities of the liquid argon TPC neutrino detector technology that will be used for DUNE
- Emphasizes the importance of the rest of the SBN neutrino program with ICARUS and SBND to resolve/confirm neutrino anomalies



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Neutrino result heralds new chapter in physics

By Pallab Ghosh
Science correspondent

27 October

FERMILAB/REIDAR HAHN

Microboone's 12m-long detector is contained inside a large cryogenic tank, filled with 150 tonnes of liquid argon at -186C

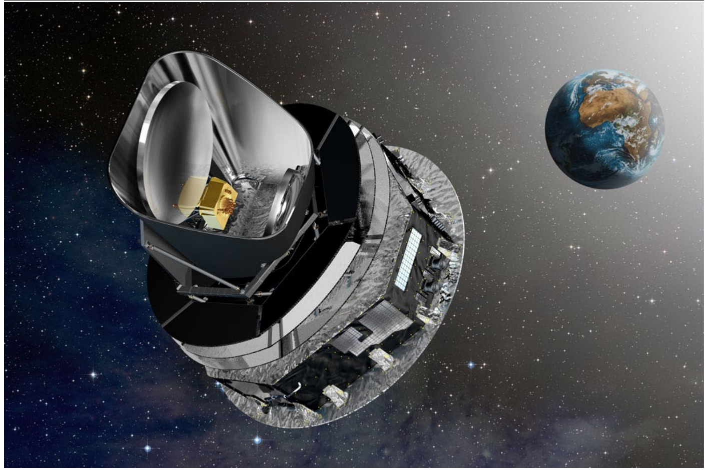
Discoveries: Cosmic

What happened

2013-2019: data from the Planck Satellite (European Space Agency) and the Dark Energy Survey (Fermilab) telescope and other sources confirm multiple precision tests of the ΛCDM concordance model of cosmology

Significance

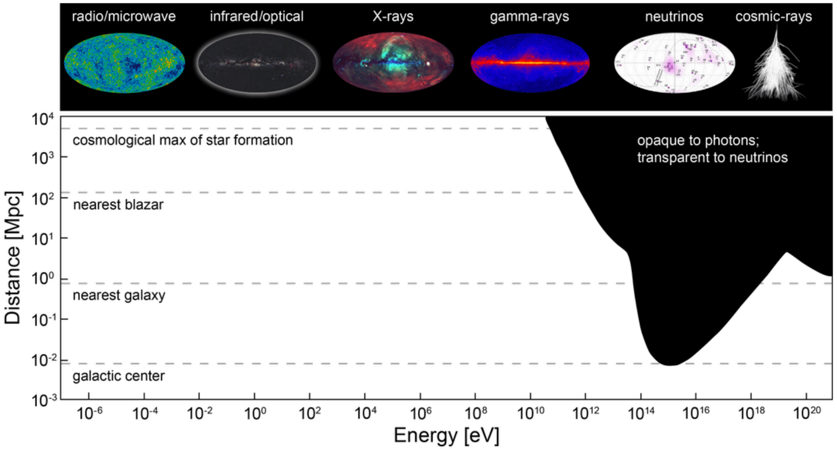
Established ΛCDM as the Standard Model of cosmology



Discoveries: Cosmic

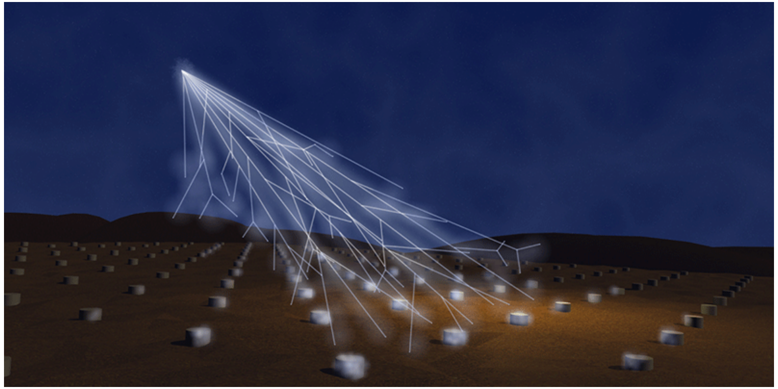
What happened

2016, 2017: the Pierre Auger observatory (Fermilab) shows that the highest energy cosmic rays originate from outside our galaxy; the IceCube neutrino observatory (NSF) confirms that the primary source of these highest energy cosmic rays are nuclei, not protons



Significance

Understanding Nature’s particle accelerators, and the composition of the highest energy collisions that we have access to



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Discoveries: Cosmic

What happened

2022: the Event Horizon array of 11 radio/microwave telescopes, including the South Pole Telescope (Fermilab+NSF), release the first image of the shadow of the supermassive black hole at the center of our galaxy

Significance

Main mission of SPT-3G is fine-grained observation of the CMB, but the identity and origin of supermassive black holes is also a major issue for cosmology


"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXXI .... No. 59,422 — NEW YORK, FRIDAY, MAY 13, 2022 — $3.00

Finland Pledges to Join NATO, Moving Alliance To the Russian Border

Decision Brings Threats From Moscow — New Sign of Putin Miscalculation

By STEVEN ERLANGER and NORIMITSU ONISHI

A funeral for Maksym Yakovenko, 41, a Ukrainian soldier who was killed by shelling, on Thursday in Bucha, northwest of Kyiv.

PANEL SUBPOENAS FIVE IN CONGRESS

A Demand for McCarthy to Testify About Jan. 6

By LUKE BROADWATER and EMILY COCHRANE

They Were 'Desperadoes,' and Middle Schoolers

Florida Juvenile System Is Blamed for Failing Children in Its Care

By FRANCES ROBLES

First Visual Journey to the Center of Our Galaxy

By DENNIS OVERBYE

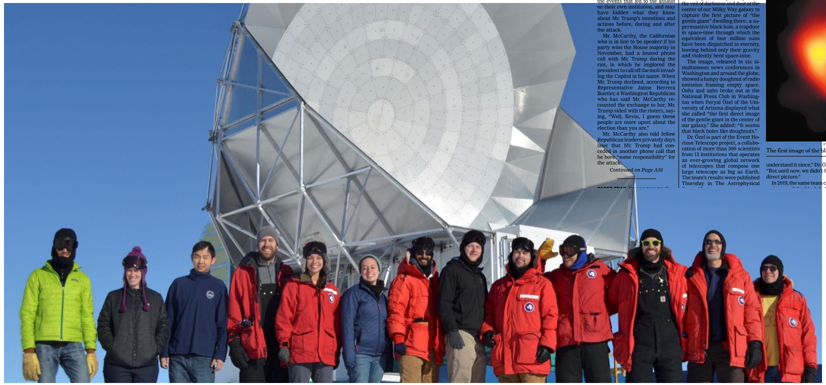
The first image of the black hole at the center of the Milky Way.

Documents recovered from Russian troops in Donetsk.

Donation to U.K. Conservatives Is Traced to a Russian Account

By JANE BRADLEY

As Cryptocurrencies Melt Down, $300 Billion Evaporates in Days



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Discoveries: Precision measurements

What happened

2021: the Fermilab Muon g-2 experiment initial results confirm the anomalously large value of the magnetic moment of the muon seen 20 years before at Brookhaven

Significance

If the final SM theory and experimental values remain discrepant, implies new particles or forces

Editorial Board

Why Congress Should Care About the Laws of Physics

Recent research seems to challenge the fundamentals of the field. The U.S. should support the quest for answers.

By Michael R. Bloomberg

May 7, 2021, 4:00 AM CDT

"The most extraordinary event of the year"- Michael Bloomberg


"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXX .... No. 59,022 — NEW YORK, THURSDAY, APRIL 8, 2021 — $3.00

Biden Tax Plan Aims to Curtail Use of Havens

Loophole Has Enriched Global Corporations

Contagious Variant Is Fueling Surge in Infections Across the U.S.

PAIR OF SETBACKS FOR ASTRAZENECA OVER ITS VACCINE

BLOOD CLOT CONCERNS

U.K. Curbs Use by Adults Under 30 as the E.U. Outlines Risks

ISIS and African Militants Join In a Marriage of Convenience

Terrorist Group Using Attacks on Continent to Raise Its Profile

New York to Provide $2.1 Billion For Undocumented Immigrants

Covid Relief Plan Riles G.O.P. and Worries Some Democrats

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

Adventurers Fleeing Pandemic Strain the West's Rescue Teams

By ALI WATKINS

A trail in the Wind River Range in western Wyoming.

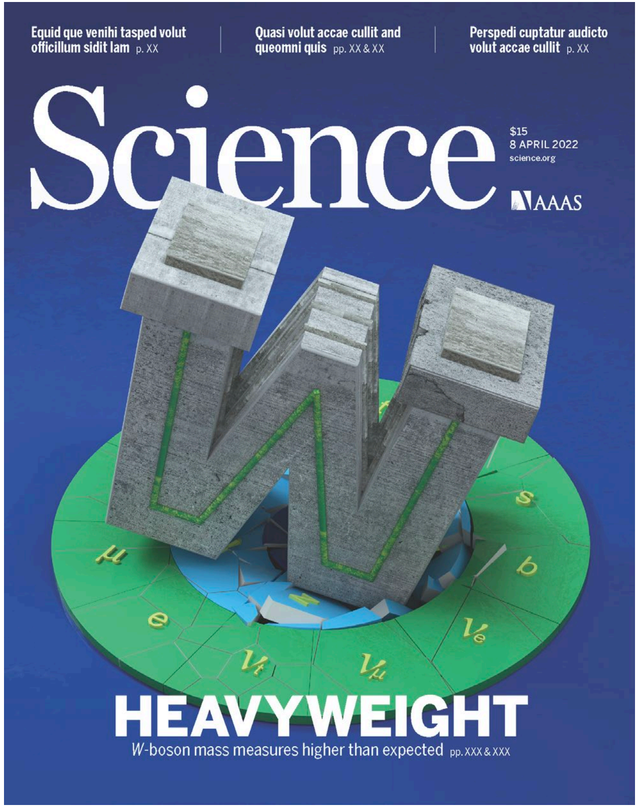
Discoveries: Precision measurements

What happened

2022: the Fermilab CDF experiment announces their final measurement of the mass of the W boson, significantly heavier than predicted by the SM

Significance

If confirmed in upcoming LHC measurements, implies new particles or forces

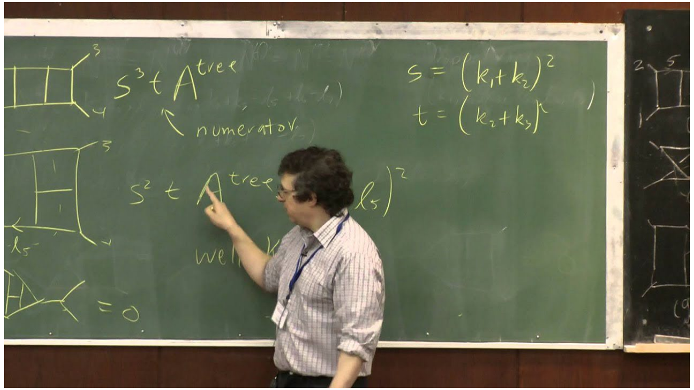


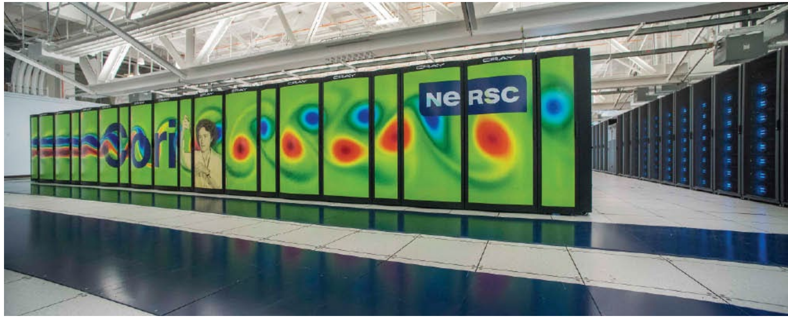
Discoveries: Theory

What happened

Ongoing: Powerful new methods allow computation of higher order effects of the SM, observed in data at LHC and elsewhere, folded into simulations, now part of the standard toolbox, adapted also for LIGO

Ongoing: Lattice gauge theory makes multiple confirmed SM predictions with percent level systematics from first principles strongly interacting QCD





Significance

These techniques essential for understanding data from LHC, B factories, and elsewhere

Discoveries: Theory

What happened

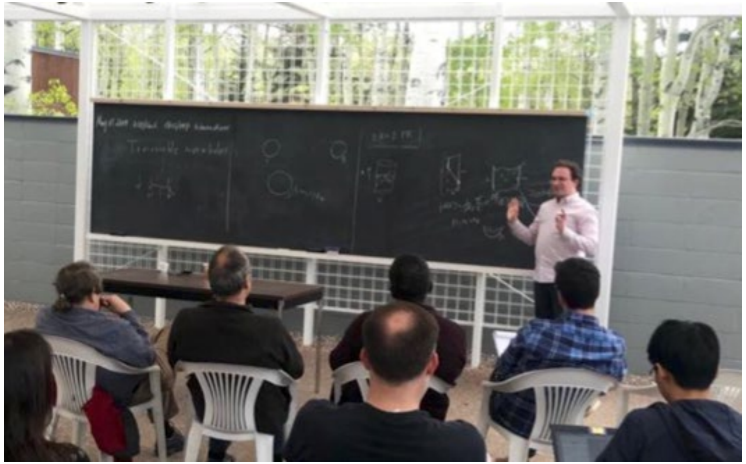
2010-now: Using AdS/CFT, theorists exploring the idea that classically connected spacetimes are an emergent phenomenon of quantum entanglement

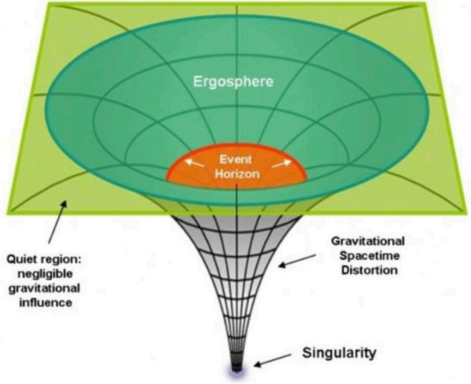
2016: conclusive demonstration of the possibility of traversable wormholes

2019: discovery of a promising theoretical solution to the black hole information loss problem

Significance

Intersection of quantum gravity and quantum information may become both a theory revolution and a route to laboratory experiments for quantum gravity





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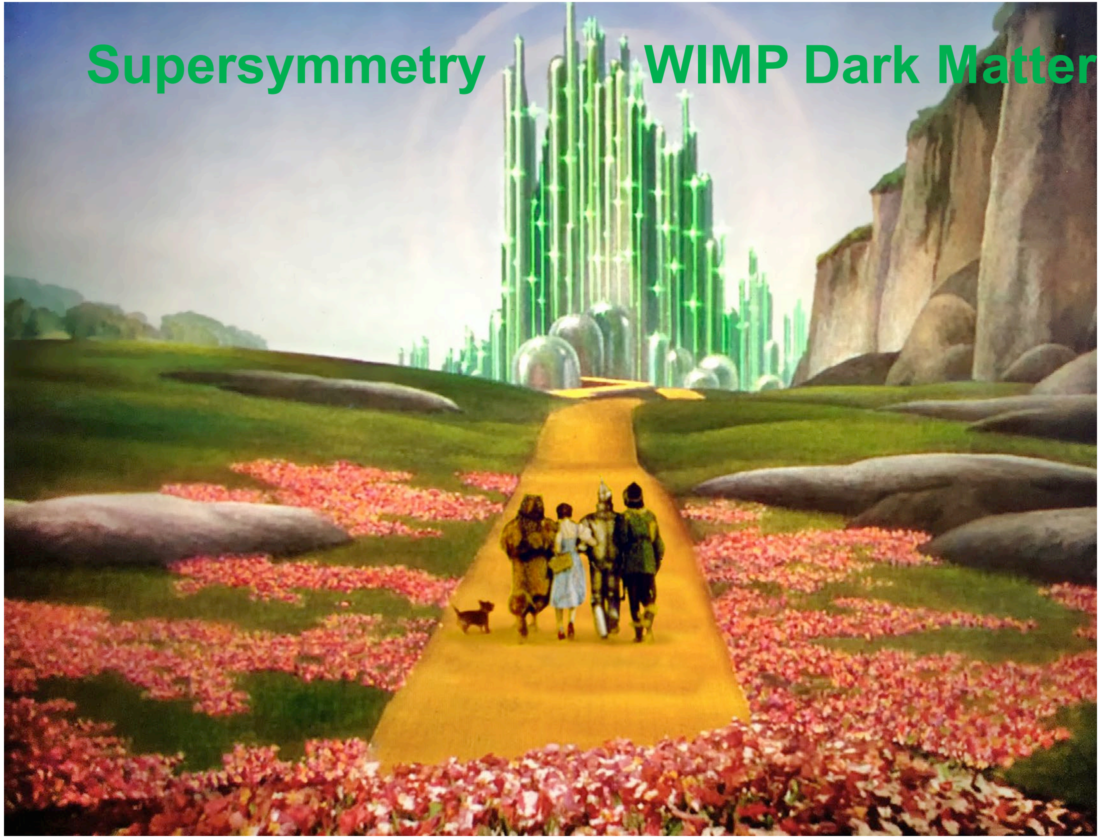
Discoveries: The dogs that did not bark

- No evidence ***so far*** at the LHC experiments of supersymmetry or other new physical mechanisms that could explain why electroweak symmetry breaking happens
- No confirmed direct detection ***so far*** of dark matter in a laboratory experiment
- No evidence ***so far*** that dark energy is dynamical rather than vacuum energy
- No evidence ***so far*** for primordial gravity waves from cosmic inflation, either in CMB B mode polarization or CMB non-Gaussianities
- No detection ***so far*** of electric dipole moments (and thus CP violation) for the electron, neutron, etc
- And many more…

Consensus HEP view of the road ahead: 2010



Consensus HEP view of the road ahead: 2022

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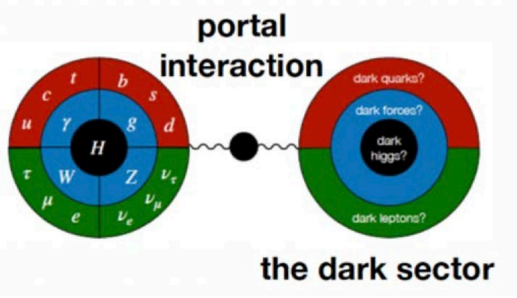
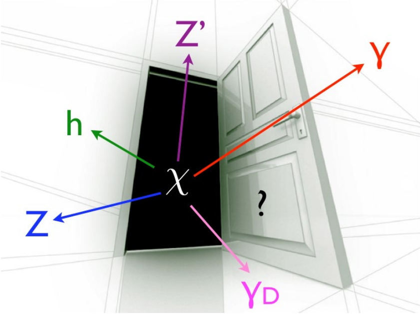
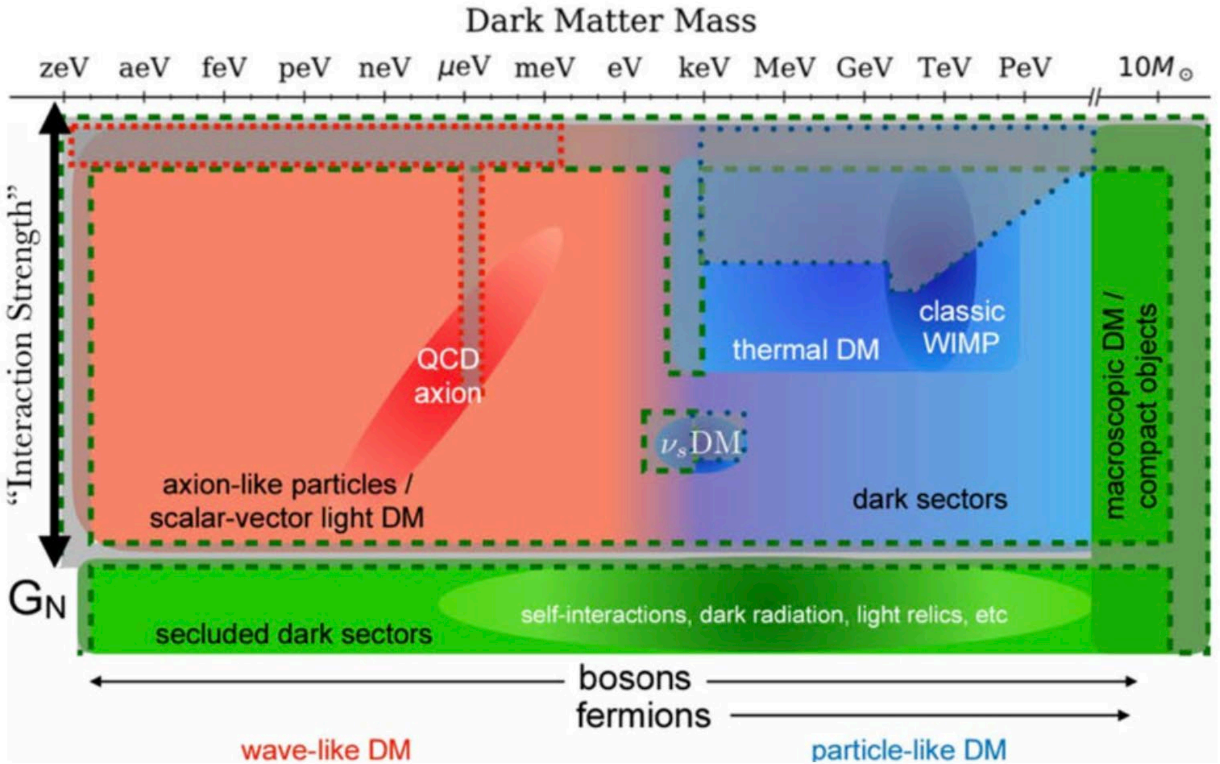
example for discussion: how has the HEP view of dark matter searches evolved since 2010?







Technology advances in particle physics since 2010

The virtuous circle between challenging basic science and technology innovation

All of the easy experiments in particle physics were already done a long time ago.

Everything that we are doing now is, to first approximation, impossible.

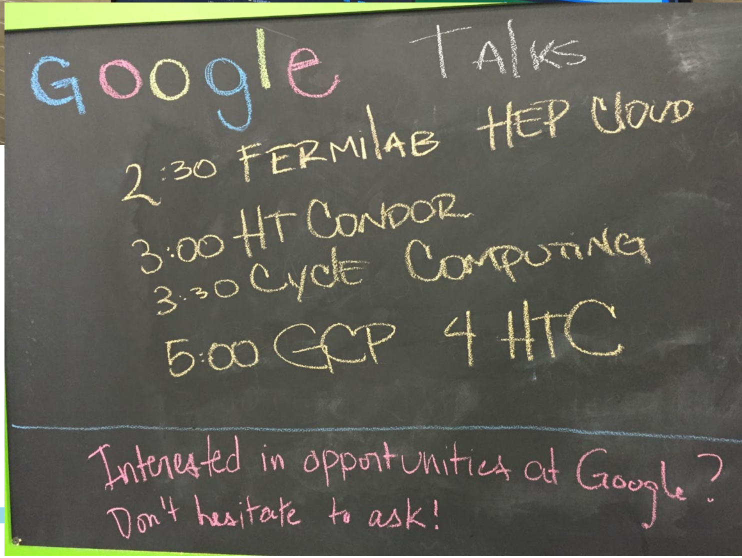
- Sometimes a new technology breakthrough will make possible a new particle physics experiment.
- HEP scientists are early adopters of new technologies or first to use on a larger scale.
- And many times, we push the technology advances ourselves, to make our experiments work.

Full deployment at a global scale of distributed “grid” computing for LHC

HEP innovated on high throughput, large CPU solutions with secure data provenance - because we had to

HEP later helped commercial cloud providers learn how to do it

HEP also pushing the boundaries of edge computing in extreme environments for triggers at LHC



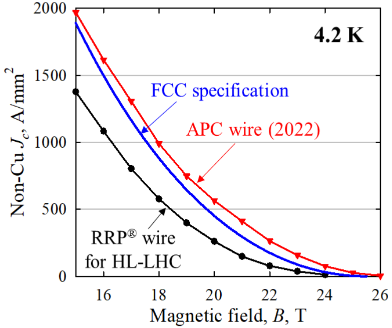
World leading advances in superconducting technologies

HEP leads the world in high gradient high Q SRF, deployed now for the LCLS-II light source at SLAC

HEP leading the development of Nb_3Sn superconductor technology

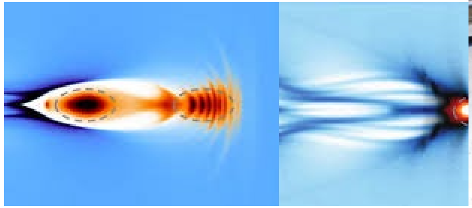
Technologies essential for HL-LHC and FCC, and are now the focus of quantum processor development at the SQMS National Quantum center

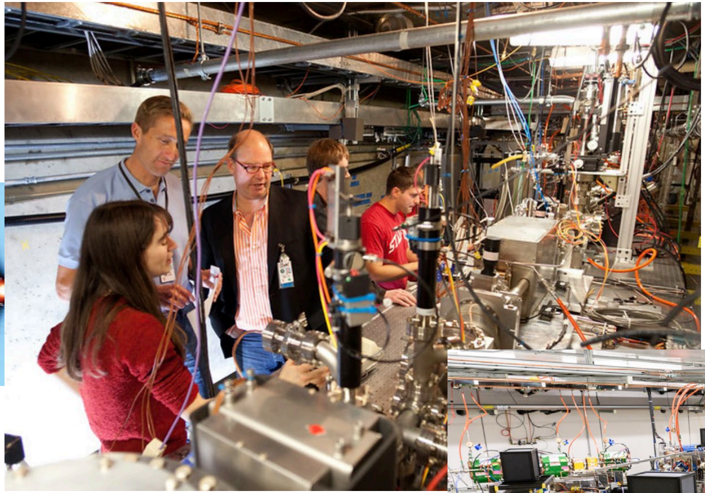
High temperature superconductor inserts



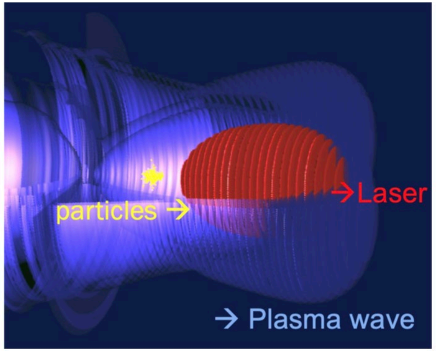
Accelerator advances for the future

Plasma and laser wakefield accelerators

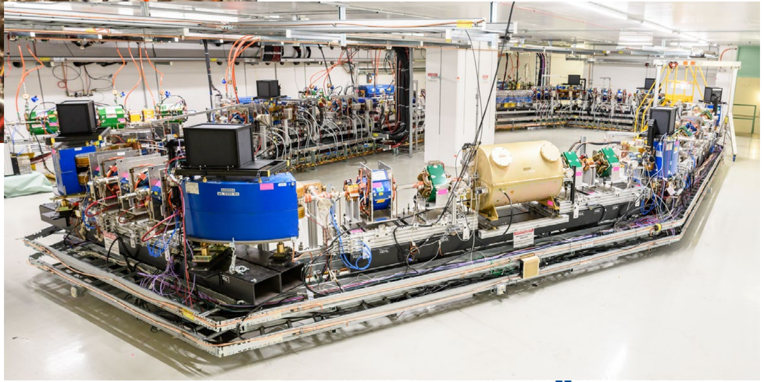




Laser driven plasma wave



Optical stochastic cooling achieved at the IOTA test acclerator



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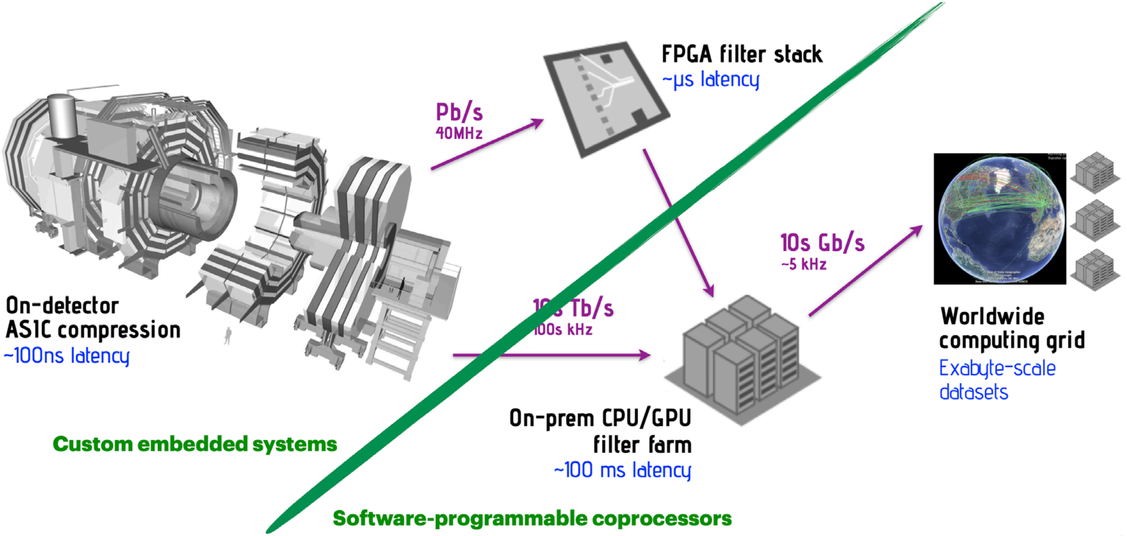
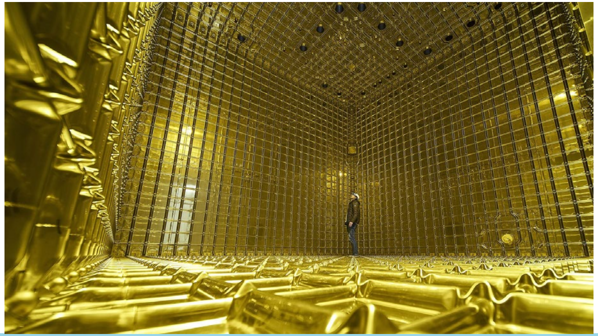
Large scale advanced detectors

200 meters^2 of silicon tracking in a single detector at LHC

"Fast AI" built into triggers for CMS



Large liquid argon TPCs with automated event reconstruction (MicroBooNE) and advanced light collection systems e.g., ARAPUCAS for DUNE, and SNSPDs



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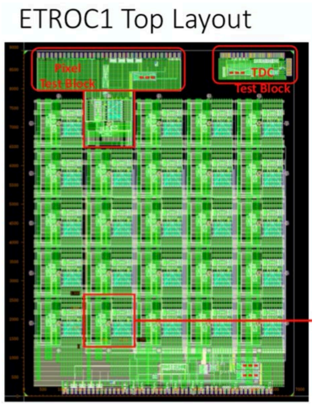
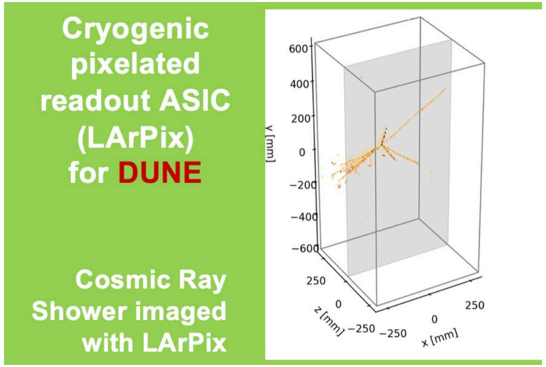
World leading microelectronics

ETROC chip for CMS is first example of “AI on a chip”



Sensors on a chip

Cryogenic electronics (collaboration with Microsoft)



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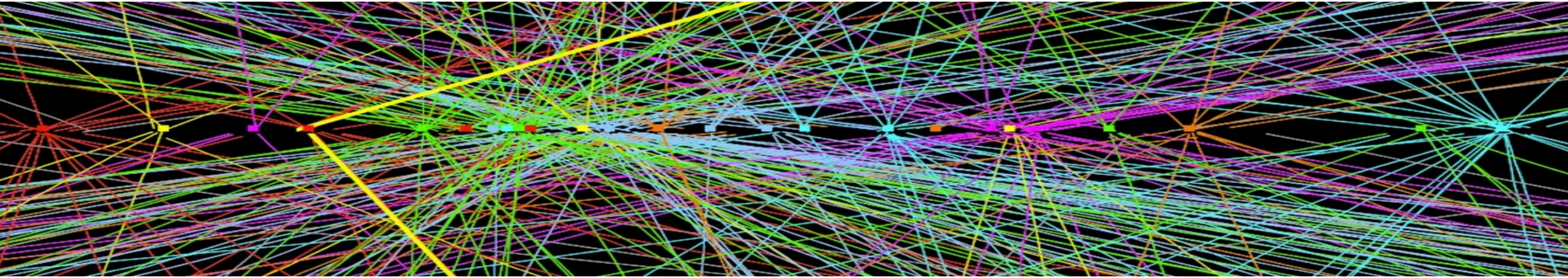
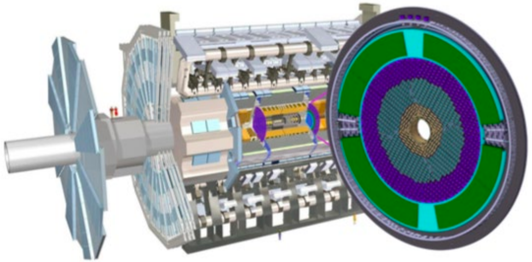
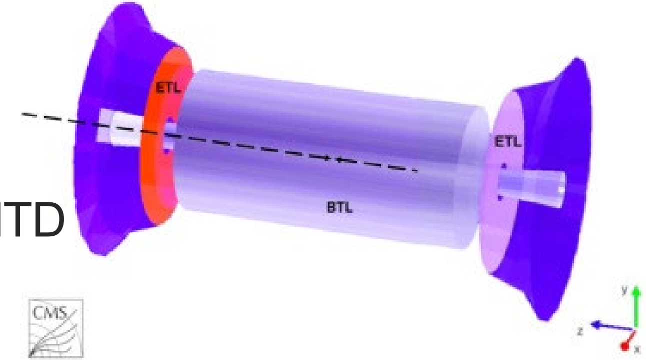
Picosecond timing for 4D detectors at HL-LHC



ATLAS HGTD



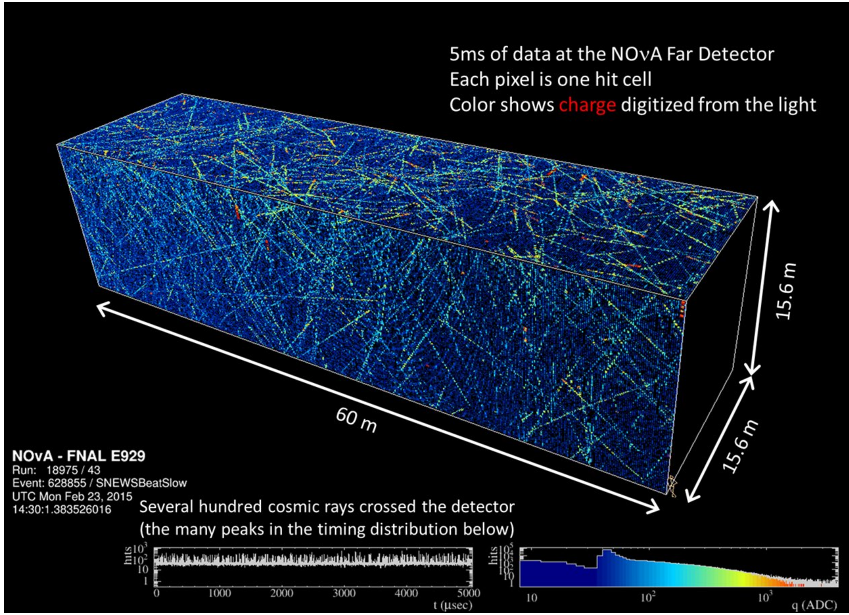
CMS MTD

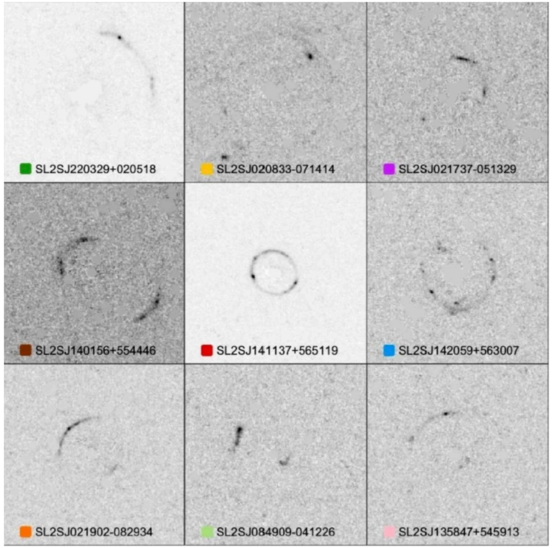


Precursors for fully 4D detectors of the future

AI/machine learning for HEP

2016: Convolutional neural network improves by 40% the true positive rate for identifying electron neutrino events in the NOvA detector, equivalent to adding 5,000 tons of detector mass





2017: HEP scientists figure out how to use AI to analyze gravitational lensing images 10 million times faster than previous methods

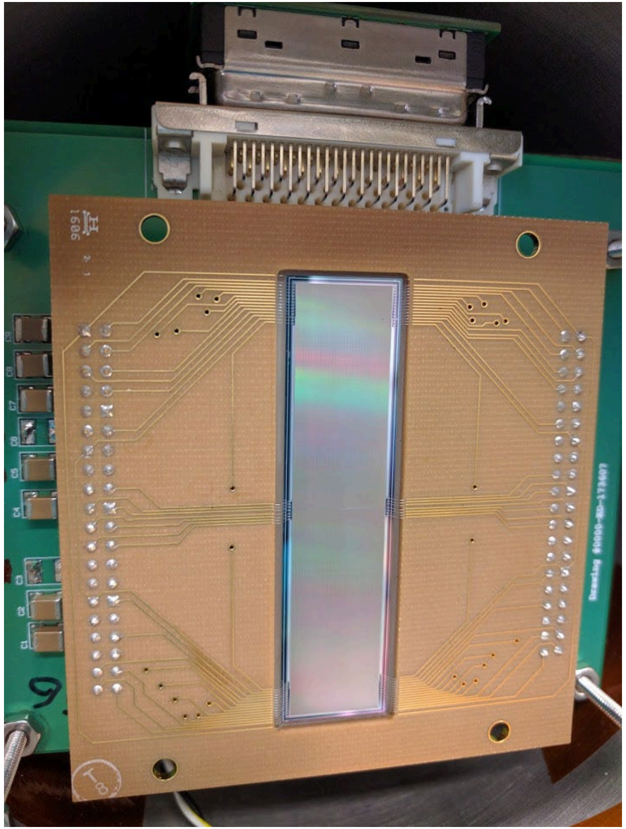
Fermilab

Skipper CCD detectors

2016: Skipper CCDs with less than single electron noise developed jointly by HEP scientists at LBNL and Fermilab

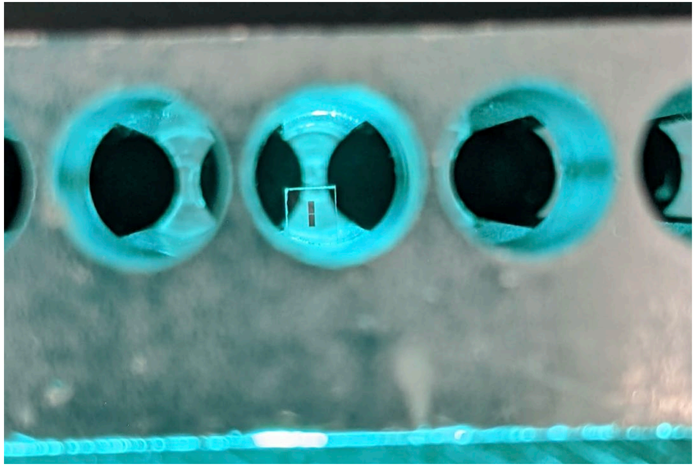
2018: The first prototype SENSEI dark matter detector made of a single 0.1 gram skipper CCD sets world's best limits on light dark matter in a mass range around 1 MeV

2021: The SENSEI scientists awarded the New Horizons Prize from the Breakthrough Prize Foundation

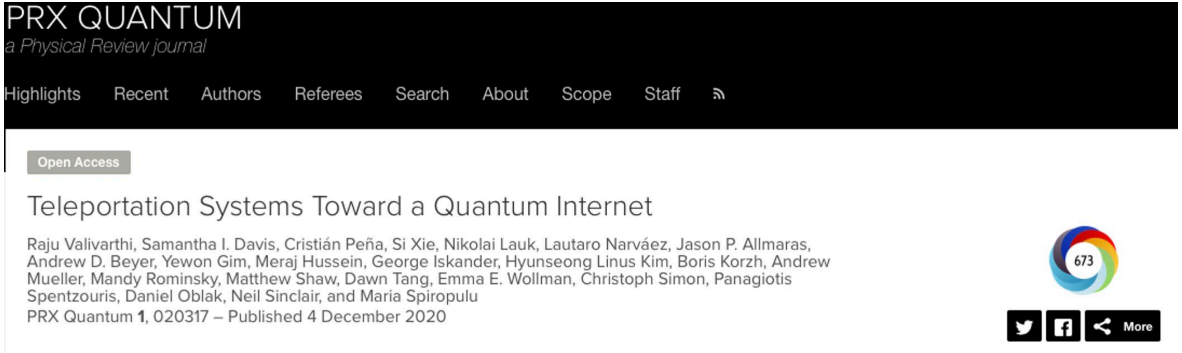


Quantum sensors, quantum teleportation

2021: HEP scientists use transmon qubit in a microwave cavity to achieve world record quantum sensor noise suppression 37x below the standard quantum limit for single microwave photon detection and world-leading dark photon sensitivity



2020: HEP scientists deploy the first sustained high fidelity quantum teleportation system



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Teleportation Systems Toward a Quantum Internet

Raju Valivarthi, Samantha I. Davis, Cristián Peña, Si Xie, Nikolai Lauk, Lautaro Narváez, Jason P. Allmaras, Andrew D. Beyer, Yewon Gim, Meraj Hussein, George Iskander, Hyunseong Linus Kim, Boris Korzh, Andrew Mueller, Mandy Rominsky, Matthew Shaw, Dawn Tang, Emma E. Wollman, Christoph Simon, Panagiotis Spentzouris, Daniel Oblak, Neil Sinclair, and Maria Spiropulu

PRX Quantum **1**, 020317 – Published 4 December 2020

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More

Evolution of the HEP program since 2010

2011: Shutdown of the Tevatron collider

- Together with the 2008 shutdown of the SLAC B-factory, this marked the end of U.S. hosted collider experiments
- The U.S. collider community, with support from DOE and NSF, largely migrated to the LHC
- Fermilab had already become the host for U.S. CMS, and the other four HEP labs support U.S. ATLAS
- During the period roughly 2000 – now, U.S. particle physics grew a substantial community devoted to Neutrino Science and another devoted to Cosmic Science.
- The U.S. LHC contingent is still the largest however

2013/2014: U.S. HEP community unites for Snowmass/P5


Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context
Executive Summary

Particle physics community unified behind the P5 plan: 2,331 signatures on letter sent to Secretary Moniz

As we plan for the future, the P5 report recommendations and the strong community support for them are forefront in our considerations.

Sincerely,

Patricia M. Dehmer
Acting Director, Office of Science

cc: Dr. Nick Hadley
Dr. Ian Shipsey
Dr. Raymond Brock

P5 headline: Particle Physics is Global

2015: Renewal of the U.S.-CERN agreement

"CERN acts as the facilitator and gate opener for the European particle physics community, so having them as a partner on neutrinos merges the ambitions of U.S. and European neutrino physicists in the best possible way."… J. Lykken, New York Times, May 7, 2015

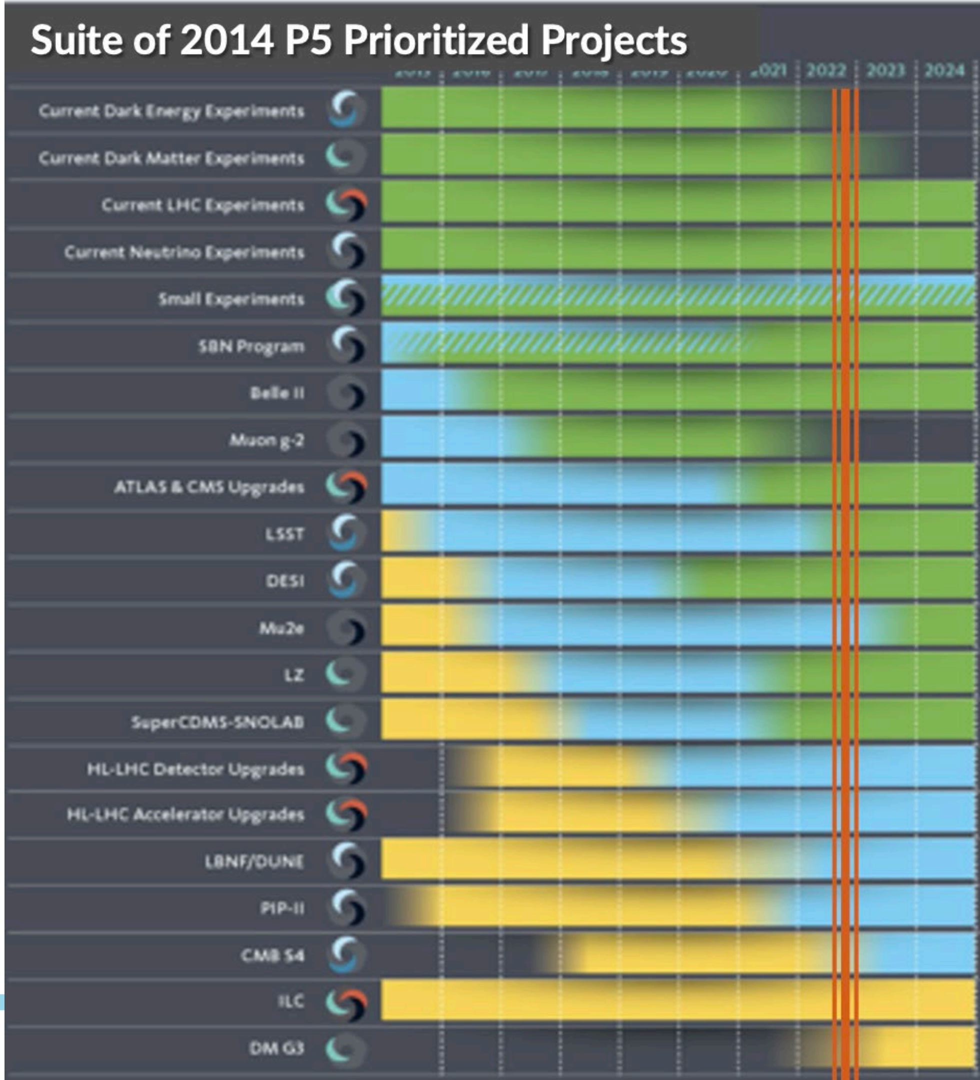
For LBNF/DUNE, PIP-II and SBN programs, 13 government-to-government agreements, and 17 DOE international CRADAs

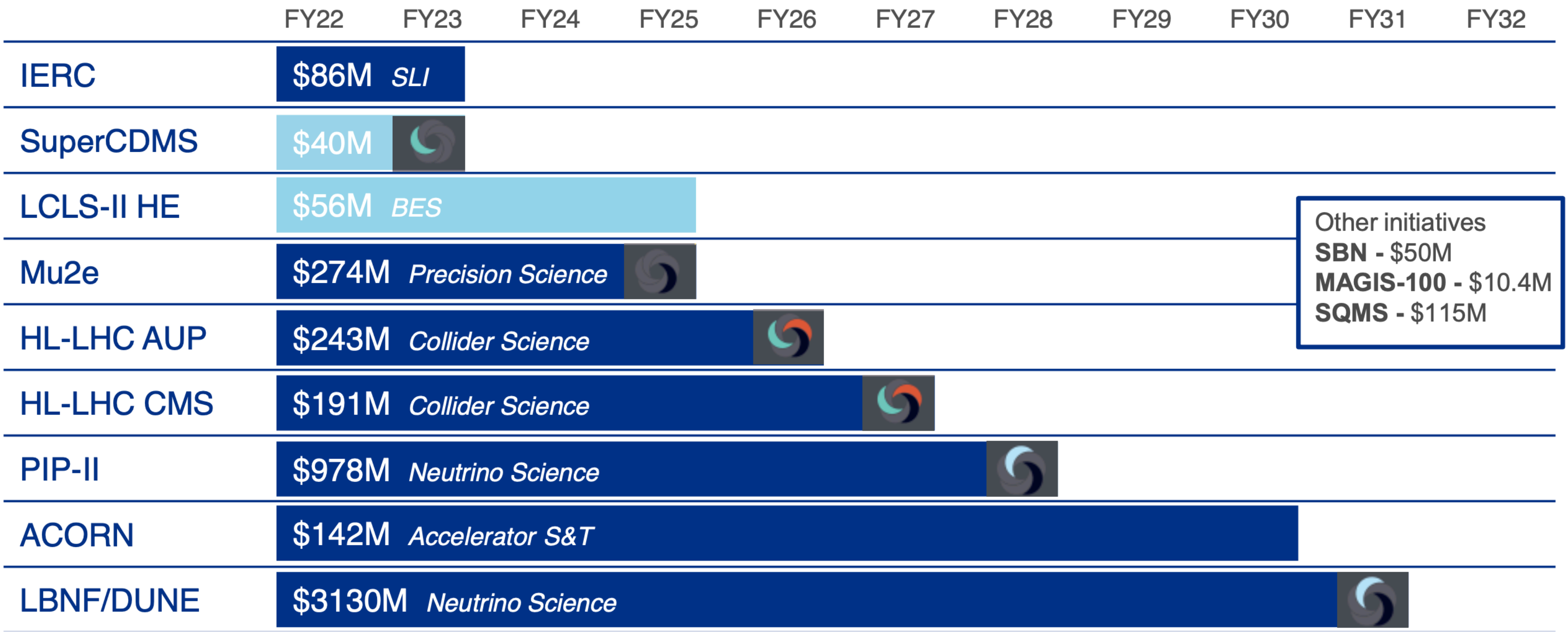
Some HEP program challenges

- The progress of the U.S. particle physics community on diversity, equity, and inclusion during the period 2010-2022 was poor, both in the absolute sense and relative to other fields. If no substantial improvement soon, this is an existential risk.
- The P5 strategy of emphasizing projects led to a greater than 50% increase in the DOE HEP budget. However, the research fraction has declined to 38%, which is too low, while project costs have increased.
- China and Russia: things will get worse before they get better.
- Sustainability: DOE labs and CERN are starting to engage on this.

Building for discovery

- Yellow = thinking about it
- Blue = building it
- Green = operating it





Other initiatives
SBN - $50M
MAGIS-100 - $10.4M
SQMS - $115M

Possible Discovery Menu in the coming decade from current program

LHC

- Higgs cousins of many types with many possible implications
- Dark matter, dark sector, feebly-interacting particles, long-lived particles
- New forces (gauge bosons)
- New kind of scalars or fermions
- Higgs boson is composite
- Higgs flavor violation, Higgs CP violation
- Lepton flavor Violation signals
- Etc.

* Some items may be related to the Muon g-2 result

* Other accelerator-based experiments will add uniquely

Fermilab

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- SBN results to make a definite statement about the MiniBooNE anomaly and its many possible BSM interpretations
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- Mass ordering to be better known from global fits, but a definitive result only possible if no tension in combined data
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Rare and Flavor

- Charged LFV
- Lepton Number violation
- Quark Flavor opportunities

Possible Discovery Menu in the coming decade from current program

Dark Matter

- Direct dark matter searches could discover one or more kinds of DM particles
- A full and varied slate of dark matter new initiatives for light DM will be in mature stages and may have discoveries
- Some fixed target accelerator-based experiments running/complete and may have discoveries

* A discovery in direct detection exp., LHC, SBN, DUNE, other accelerator-based or indirect dark matter searches, cosmic probes of DM, will have immediate implications for all other experiments. Applies both to DM and dark sector/forces

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Cosmic

- Unique probes of dark matter properties, interactions with the SM and with itself
- Even better limits or measure the sum of neutrino masses from cosmic probes
- Dark energy is dynamical
- Dynamics of inflation; primordial B-modes either observed of better constrained
- Resolve the Hubble tension, which may be an indication of physics beyond the SM
- Better measurement of N_{eff} (relevant for light relics)
- Gravitational waves as a window to early phase transitions

Fermilab

Bottom line

- U.S. particle physics has a strong growing program
- The program is both broad and international by design
- U.S. program has become oriented towards supporting the science wherever it is most appropriately accomplished: CERN, South Dakota, South Pole, Chile, etc.
- The current program has a lot of exciting discovery potential and some challenges
- The major questions of the field are **very ambitious,** thus likely to take decades more to resolve, requiring both new tools and new ideas