Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Exploring the Quantum Universe

2023p5report.org

Tulika Bose
University of Wisconsin-Madison
On behalf of the 2023 P5

U.S. DEPARTMENT OF ENERGY

NSF


Science
GET OUR E-ALERTS
COMMENTARY
JOURNALS
Current Issue
First release papers
Archive
About
Submit manuscript
Science
HOME > SCIENCE > VOL. 279, NO. 5348 > PHYSICISTS DREAM OF A MUON SHOT
CURRENT ISSUE
NEWS
Physicists Dream of a Muon Shot
Authors Info & Affiliations
DOI: 10.1126/science.279.5348.169
SCI AM
Sign Up for Our Daily Newsletter
DECEMBER 13, 2023 | 8 MIN READ
Road Map for U.S. Particle Physics Wins Broad Approval
A major report plotting the future of U.S. particle physics calls for cuts to the beleaguered DUNE project, advocates a “muon shot” for a next-generation collider and recommends a new survey of the universe's oldest observable light
BY DANIEL GARISTO
nature
Explore content
About the journal
Publish with us
Subscribe
nature > news > article
NEWS | 07 December 2023
Big Bang observatory tops wish list for big US physics projects
Report also supports projects of unprecedented scale to study dark matter, neutrinos and the Higgs boson.
By Davide Castelvecchi
Physics
Technology
Community
In focus
Magazine
Jobs
POLICY | NEWS
US unveils 10-year strategy for particle physics
11 January 2024
CERNCOURIER
Keep in touch: follow us on Twitter
SHARE
FYI / ARTICLE
Particle Physics Panel Assesses US Influence on Global Stage
DEC 01, 2023
Andrea Peterson
Related Topics
MAJOR REPORTS
INTERNATIONAL AFFAIRS
The New York Times
Particle Physicists Agree on a Road Map for the Next Decade
A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.
nature
Explore content
About the journal
Publish with us
Subscribe
nature > editorials > article
EDITORIAL | 17 January 2024
US particle physicists want to build a muon collider – Europe should pitch in
A feasibility study for a muon smasher in the United States could be an affordable way to maintain particle physics unity.
CBS NEWS
Latest
Local News
Live
Shows
CHICAGO
News
Weather
Sports
Video
LOCAL NEWS
Report on future of particle physics outlines exciting scientific priorities
CBS 2 NEWS

What Is P5?

Particle **P**hysics **P**roject **P**rioritization **P**anel

- Subpanel of the High Energy Physics Advisory Panel (HEPAP), which advises the Department of Energy and the National Science Foundation on issues related to theoretical and experimental particle physics & associated technologies (accelerators, advanced computing, etc.)
- P5 is created ~ once a decade and is charged with reviewing the science cases for, prioritizing proposals for projects over a ten year timespan (with a view to a longer-term future)
  - also makes other actionable recommendations for the health of the field
- Analogous to a “decadal survey” or “long-range plan”
- The previous P5 report was in 2014

Who is P5?

The P5 process

P5 takes input from the Snowmass process, a community fact-finding & planning effort led by the APS Division of Particles and Fields

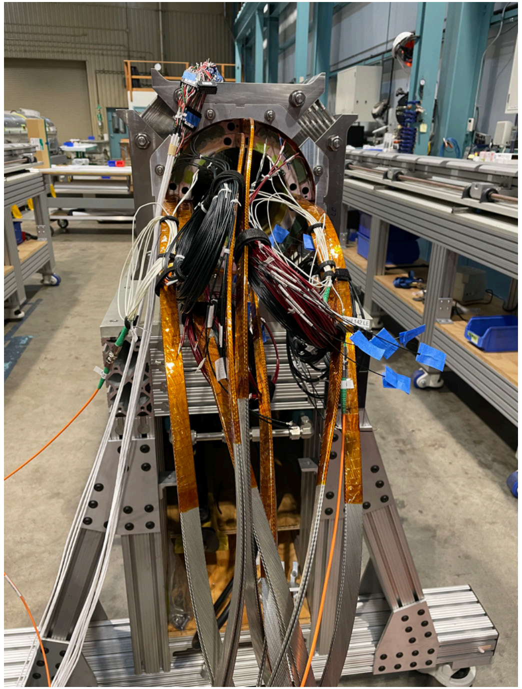
- Went on for 2 years due to COVID!

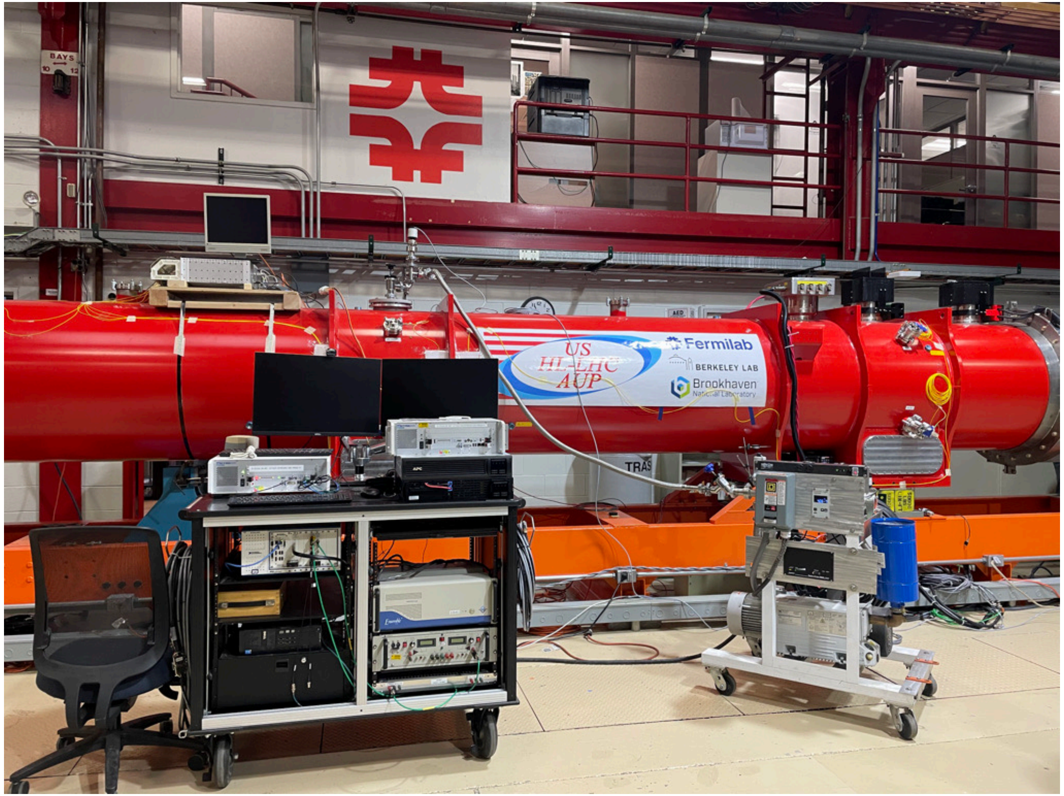
Some members of the community at the Community Summer Study in Seattle in July 2022 & Zoom

The P5 process

In 2023 we held

- Four in-person Town Halls at DOE labs

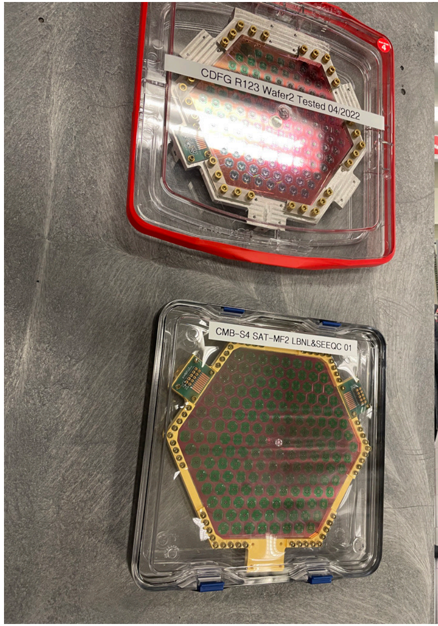


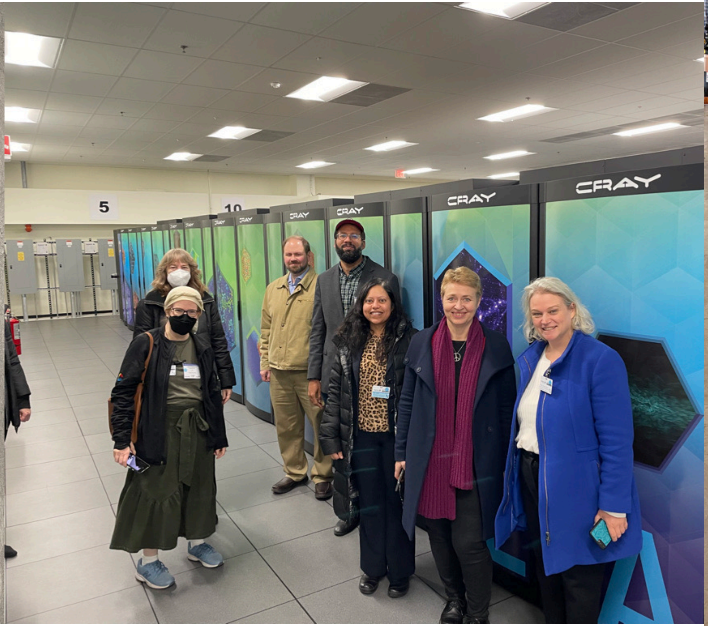


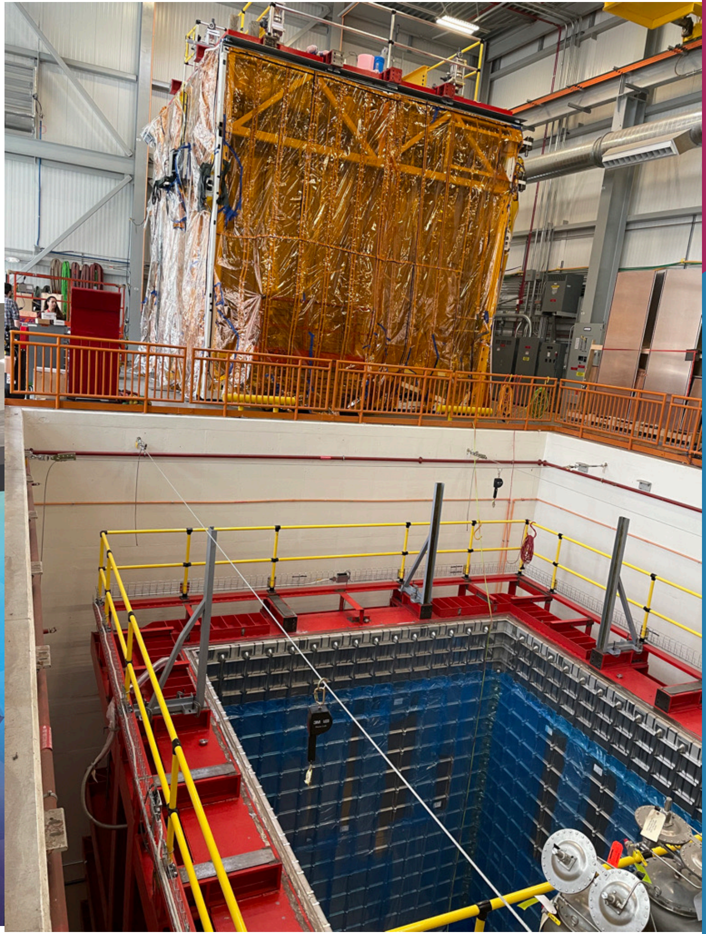
The P5 process

In 2023 we held

- Four in-person Town Halls at DOE labs







The P5 process

In 2023 we held

- Four in-person Town Halls at DOE labs
- Two virtual Town Halls
    - (including one targeting early career members)
- Four week-long in-person closed meetings
- Weekly (multiple hour) Zoom meetings from August to December

What is the P5 report? or who is it for?

- The report is a roadmap for the next decade.
- It is used by the agencies, Department of Energy and National Science Foundation, to decide what to fund in the future.
- It is used by all of us as a guidance on where to invest our precious research time.
- It is used as a guidance on what to prioritize if budgets fall in hard times.
- It is also used as an advocacy document to communicate to congress what are the priorities in the field and to argue for funding levels.

What is not? It is not an implementation of the program.
It is now up to the agencies to do the implementation and to particle physicists to advocate for it and work towards it.

What is the P5 report? or who is it for?

The enthusiasm and engagement of early career participants, both in the planning process and in recent town halls, has been truly inspiring. They are the future leaders who will bring to life the goals and aspirations outlined in this report.

We strove to carefully craft a balanced program in terms of scientific focus, project timescales, and the interplay between ongoing initiatives and the innovation essential for the future. Adhering to fiscal constraints means that not every ambitious endeavor can be immediately realized. Agile, adaptable, and forward-looking projects are essential to the balance. Sustained progress over the next decade requires enhanced investment in research, theoretical frameworks, critical infrastructure, and emerging technologies. Also crucial is the commitment to build a respectful and inclusive community. We hope the resulting program enables early career researchers to spearhead progress and shape the future.

This report is for you!

From the Preface of the P5 Report

What is "Particle Physics"?

Surprisingly difficult question!

Definition has changed with time, and differs around the world

Broadly speaking, driven by two key questions:

- **What are the fundamental types of matter and force in the universe?**
- **What are the principles that govern their interactions?**

What is “Particle Physics”?

Surprisingly difficult question!

Definition has changed with time, and differs around the world

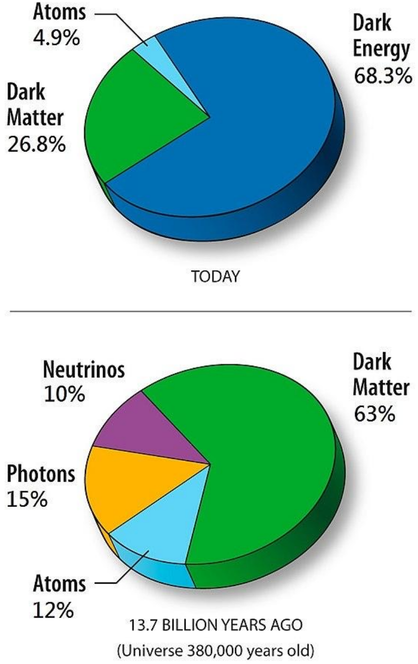
- The study of fundamental particles and the forces between them
  - protons and neutrons are composite, *not* fundamental, particles
  - their study is nuclear physics …

What is “Particle Physics”?

Surprisingly difficult question!

Definition has changed with time, and differs around the world

- The study of fundamental particles and the forces between them
- This includes the fundamental physics at the origin of the universe
    - our “normal” matter is a tiny fraction of the universe
    - there must be fundamental particles and forces that we currently detect only via astronomical/cosmological observations



What is “Particle Physics”?

Surprisingly difficult question!

Definition has changed with time, and differs around the world

- The study of fundamental particles and the forces between them
- This includes the fundamental physics at the origin of the universe

We do not include

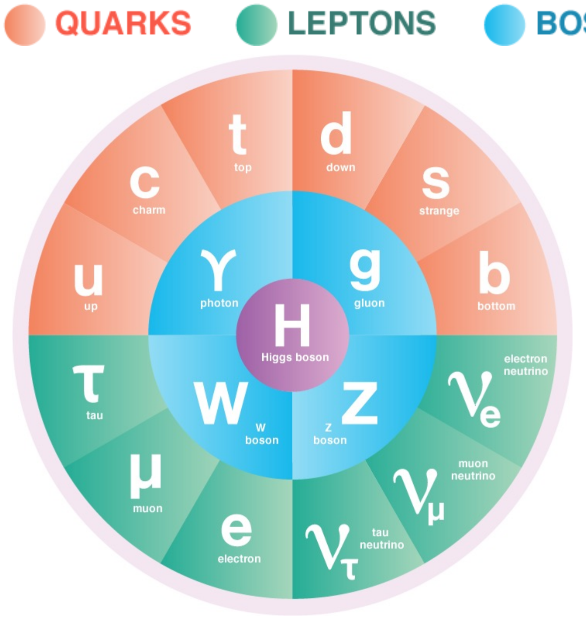
- “particle astrophysics”, e.g. astronomy with neutrinos, but experiments can overlap
- gravitational wave observatories

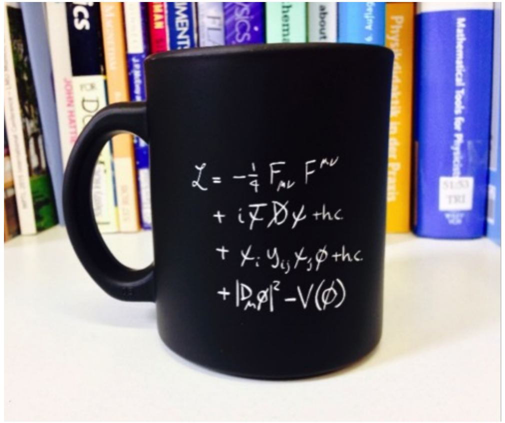
What is "Particle Physics"?

Many kinds of experiments and facilities

- colliders of different energies
- large-volume, low-noise targets for neutrinos and dark matter
- cosmological observations: cosmic microwave background, matter distribution
- "antennas" for certain kinds of dark matter
- intense sources of particles to search for rare interactions

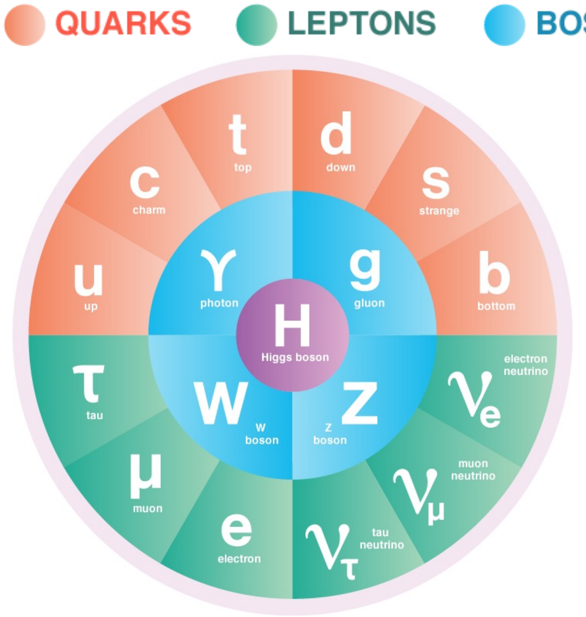
What objects are we studying?

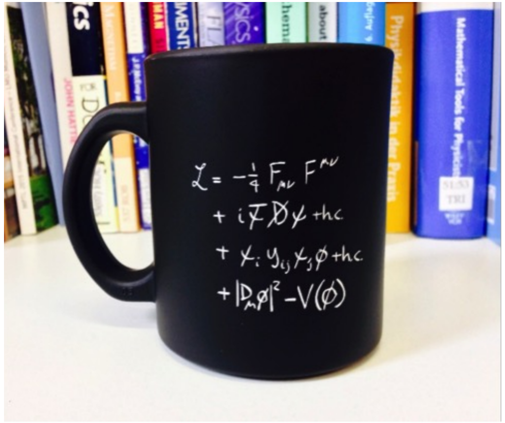




Understanding the Higgs is key, it couples to all matter particles…

What objects are we studying?





- \+ dark matter
- \+ dark energy
- \+ inflaton field
- \+ origin of neutrino masses
- \+ origin of net matter density
- \+ grand unification of forces?
- \+ unification with gravity?

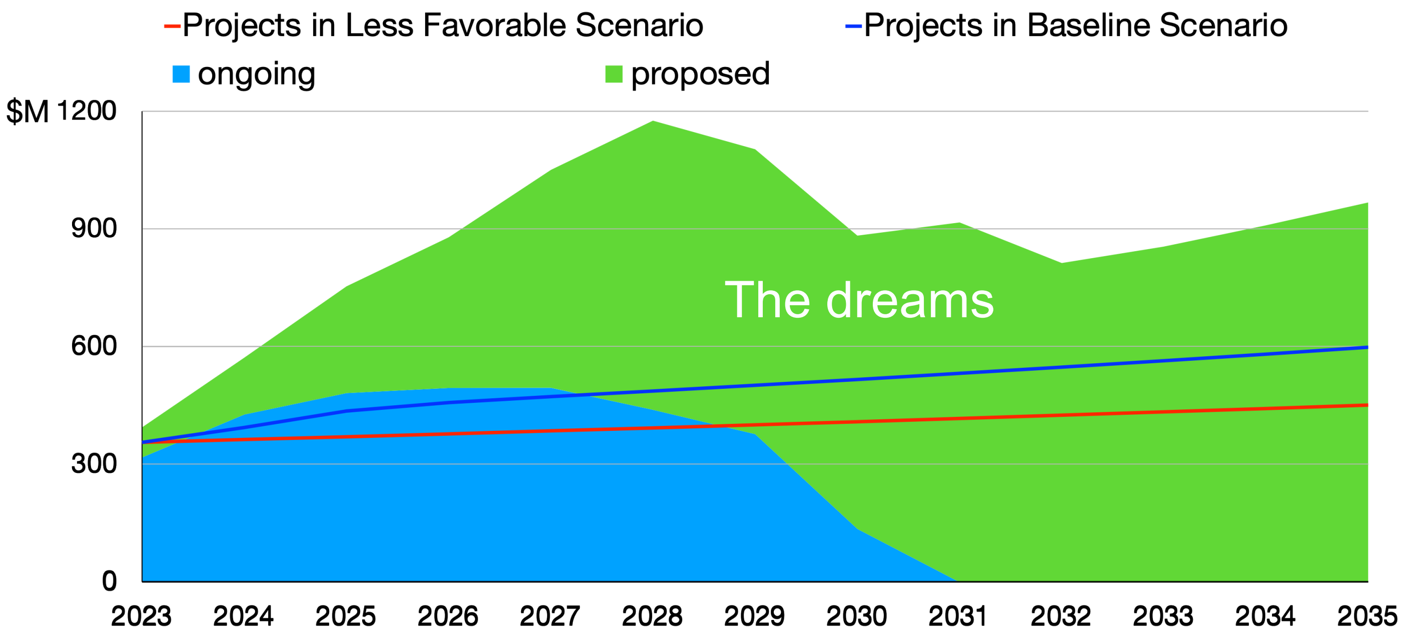
What has happened since last time?

We have learned a lot since the 2014 report:

- **We have not found new fundamental particles** outside the Standard Model. Any new collider that tries to probe higher scales *must* have a major jump in energy (~ order of magnitude).
- **Dark matter has not yet been directly observed** via interactions with normal matter, prompting the development of a rich program of experiments sensitive to alternative models to "Weakly Interacting Massive Particles" (WIMPs). There is also growing interest in studying associated "**dark sectors**."
- There are **tensions in cosmological parameters** determined by different observations - in particular with the Hubble parameter H_0 and the "clumpiness of matter" S_8. This could hint at a failure of the ΛCDM model.
- **The Higgs boson is quite similar to the one predicted by the Standard Model.** Probing its nature in detail will require exquisite precision and clean production environments.
- There remain discrepancies between theory and experiment in a number of "flavor physics" measurements which **hint at new interactions**.

This information guides shifts in the 2023 report; the big-picture science and near-term highest priorities are the same but the vision has evolved.

Of Dreams and Budgets

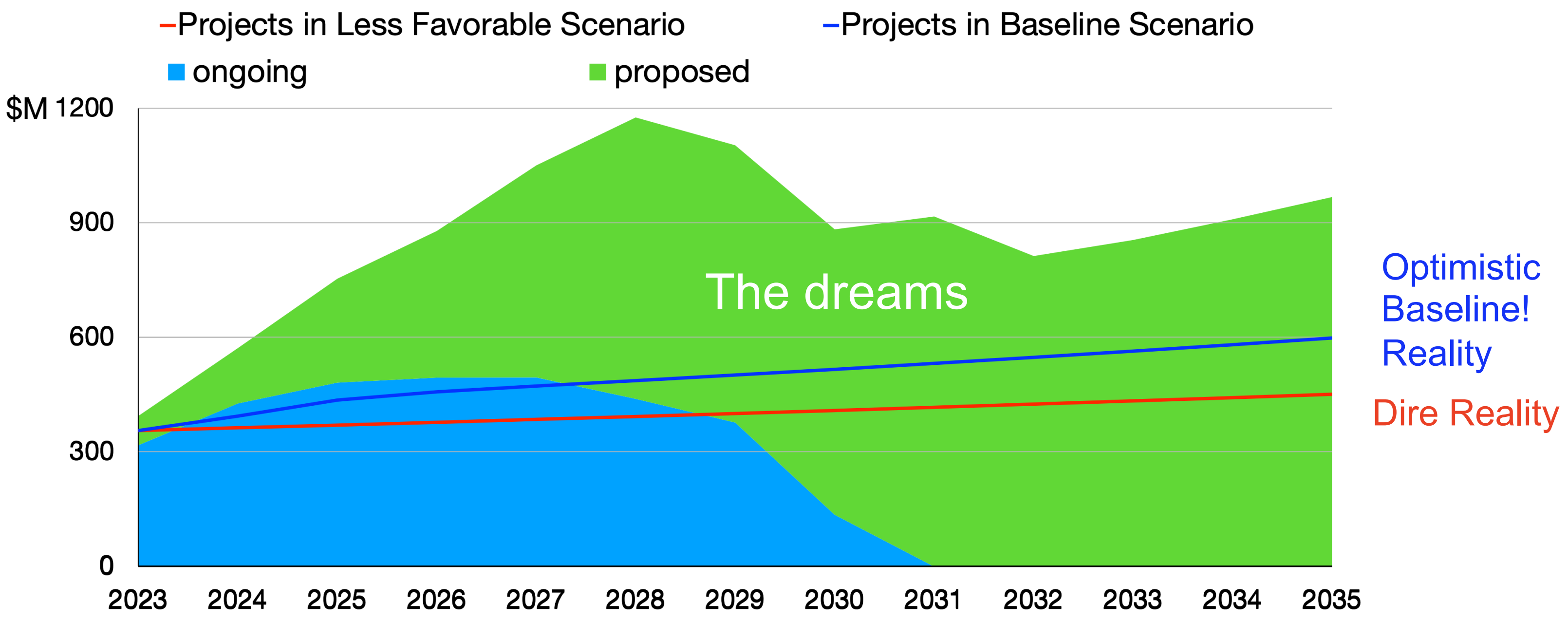


not including on-shore Higgs factory

DOE only

Wait! but where is my super-optimistic reality??

Of Dreams and Budgets



not including on-shore Higgs factory

DOE only

Report details how to move from one reality to the other

Of Dreams and Budgets

We had to consider plausible budgets for US funding (specifically, the DOE part):

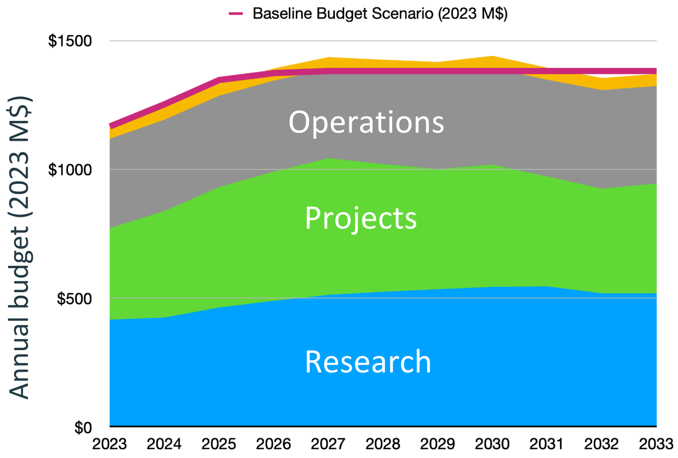
- **Baseline**: as specified in the CHIPS and Science Act, then 3% increase per year in nominal terms (so assumed flat in real dollars)
- **Less favorable**: no CHIPS Act bump, 2% increase per year in nominal dollars (so steady decrease in real terms)

The budget cannot go all to building projects - this includes funding students and postdocs, operating existing facilities, and so on. The breakdown is roughly 30-30-40 for projects, operations, and research.

Cannot do just billion-dollar-scale projects!

- Need pathfinder/demonstration experiments
- Need to train people in all stages of the experimental lifecycle

P5 recommends a dedicated, stable set-aside in DOE ("ASTAE") to fund smaller-scale projects in all particle physics areas, with annual calls for proposals.



Particle Physics in a Global Context

Some projects *require* international collaboration to proceed – no single entity has the resources (budgetary, technical, personnel) to pull them off

- CERN was the prototype for Europe, but now CERN itself needs to collaborate with other entities: the US is part of the Large Hadron Collider, CERN is part of the US neutrino program
- Negotiations across multiple planning processes and treaty-level agreements

Many projects are reasonably within a single country's scope (of course international collaboration is still helpful)

- Are they competitive with proposals elsewhere for science and timeline? Do they feed into particular strengths of the US program (unique facilities, expertise)? Do they engage with US national initiatives? Will they be effective for workforce development?

The Science

To organize our thoughts we considered overarching “science themes”:

- ***Decipher the Quantum Realm***: we have fundamental particles (neutrinos and the Higgs boson) whose properties and nature are still somewhat mysterious. Are they as simple as the particle physics Standard Model claims them to be?
- ***Illuminate the Invisible Universe***: 95% of the energy of today’s universe is not explained by the Standard Model. Yet it is quite well described by adding “dark matter” and “dark energy” whose nature is not understood. Dark energy has similarities to what causes the “inflation” era right after the Big Bang. Can we find dark matter? Can we probe the evolution of dark energy? Can we measure the behavior of inflation?
- ***Explore New Paradigms in Physics***: Are there completely new particles and forces that we don’t know of? Are the parameters of the Standard Model accidental or do they reflect selection principles?

The Science

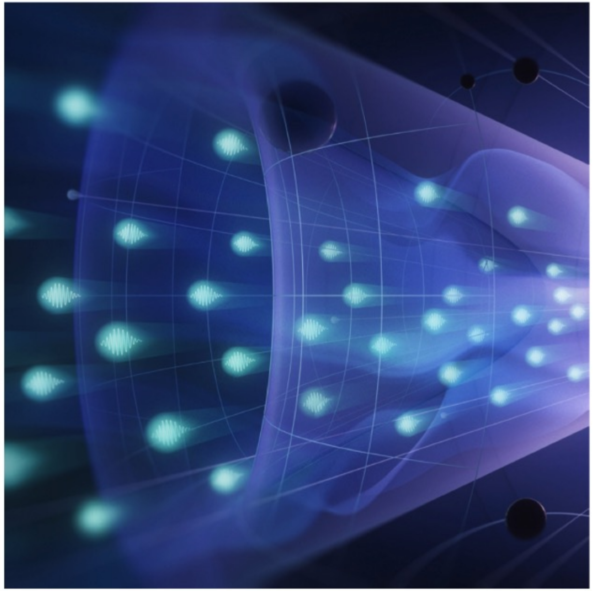
To organize our thoughts we considered overarching “science themes”:

- ***Decipher the Quantum Realm***: we have fundamental particles (neutrinos and the Higgs boson) whose properties and nature are still somewhat mysterious. Are they as simple as the particle physics Standard Model claims them to be?
- ***Illuminate the Invisible Universe***: 95% of the energy of today’s universe is not explained by the Standard Model. Yet it is quite well described by adding “dark matter” and “dark energy” whose nature is not understood. Dark energy has similarities to what causes the “inflation” era right after the Big Bang. Can we find dark matter? Can we probe the evolution of dark energy? Can we measure the behavior of inflation?
- ***Explore New Paradigms in Physics***: Are there completely new particles and forces that we don’t know of? Are the parameters of the Standard Model accidental or do they reflect selection principles?

The Science

To organize our thoughts we considered overarching “science themes”:

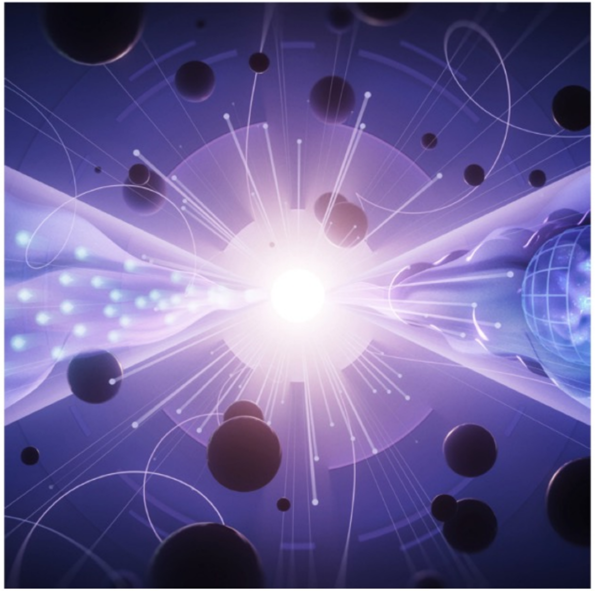
- ***Decipher the Quantum Realm***: we have fundamental particles (neutrinos and the Higgs boson) whose properties and nature are still somewhat mysterious. Are they as simple as the particle physics Standard Model claims them to be?
- ***Illuminate the Invisible Universe***: 95% of the energy of today’s universe is not explained by the Standard Model. Yet it is quite well described by adding “dark matter” and “dark energy” whose nature is not understood. Dark energy has similarities to what causes the “inflation” era right after the Big Bang. Can we find dark matter? Can we probe the evolution of dark energy? Can we measure the behavior of inflation?
- ***Explore New Paradigms in Physics***: Are there completely new particles and forces that we don’t know of? Are the parameters of the Standard Model accidental or do they reflect selection principles?



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

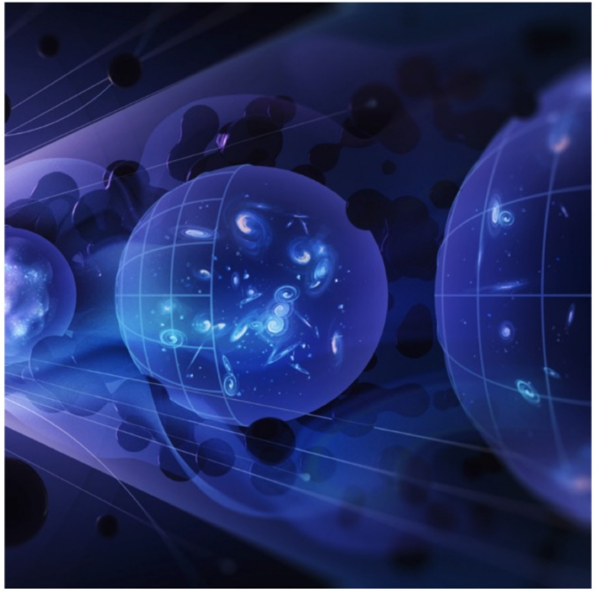
Reveal the Secrets of the Higgs Boson



Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena



Illuminate the Hidden Universe

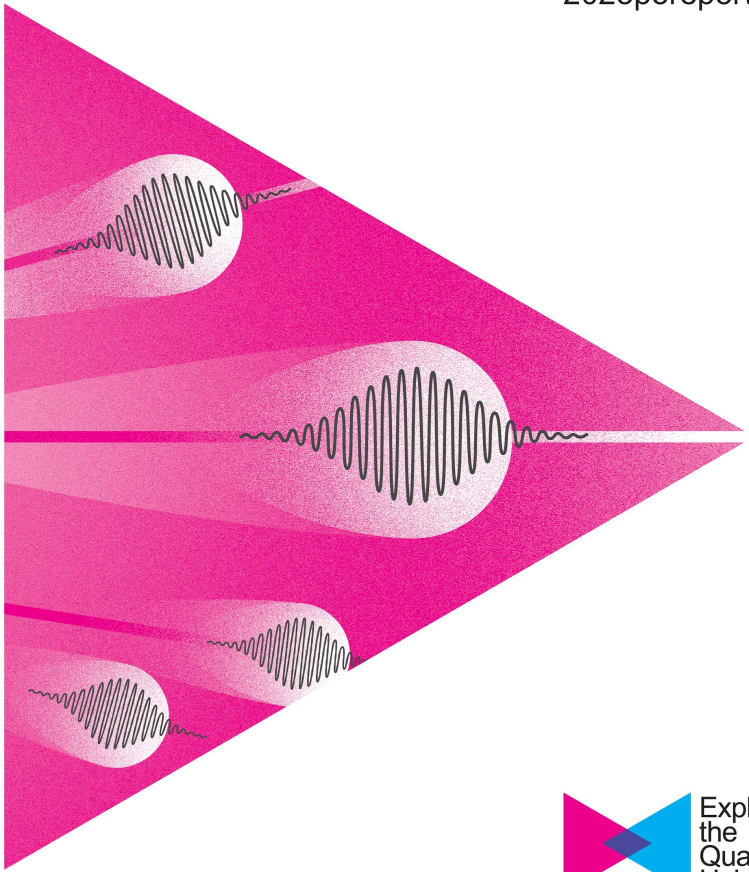
Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

What is the P5 vision?

We envision a new era of scientific leadership, centered on decoding the quantum realm, unveiling the hidden universe, and exploring novel paradigms. Balancing current and future large- and mid-scale projects with the agility of small projects is crucial to our vision. We emphasize the importance of investing in a highly skilled scientific workforce and enhancing computational and technological infrastructure. Acknowledging the global nature of particle physics, we recognize the importance of international cooperation and sustainability in project planning. **We seek to open pathways to innovation and discovery that offer new insights into the mysteries of the quantum universe.**

From the 1.1 Overview and Vision of the P5 Report



Elucidate the Mysteries of Neutrinos

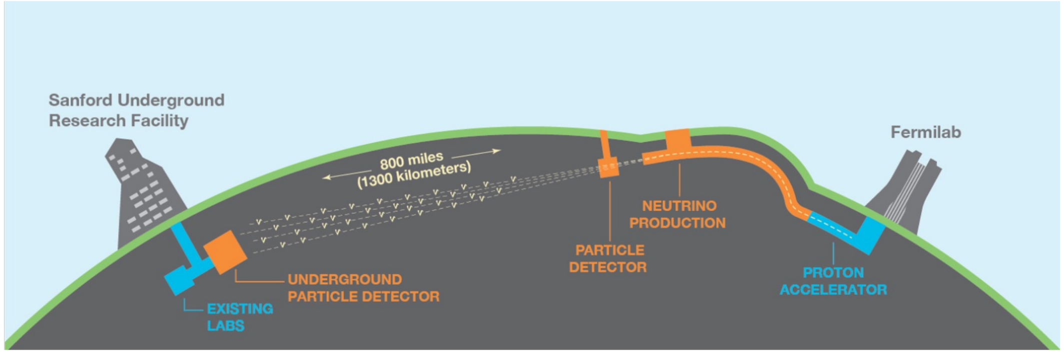
Exploring the Quantum Universe

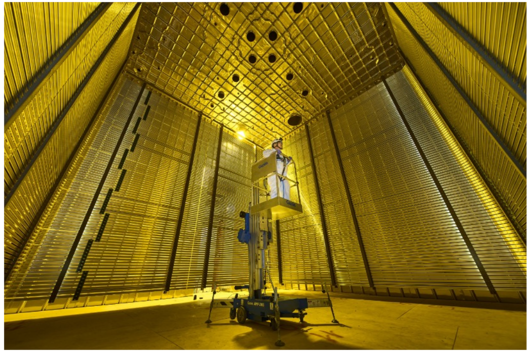
Neutrinos: Ghostly Messengers

Neutrinos are pervasive, weakly interacting, and strangely light.
The weakness of their interactions makes them extremely difficult to study.
Fundamental things we do not know:

- Which of the three neutrinos is the heaviest (**mass ordering** or **hierarchy**)
- The **actual masses** of the neutrinos (we know the differences of the squared masses)
- Whether antineutrinos and neutrinos **behave the same way**
- How exactly the different neutrinos **mix** with each other
- Whether there are additional **“sterile” neutrinos**
- **Are neutrinos their own antiparticles**? (for various reasons, considered nuclear physics in the US)

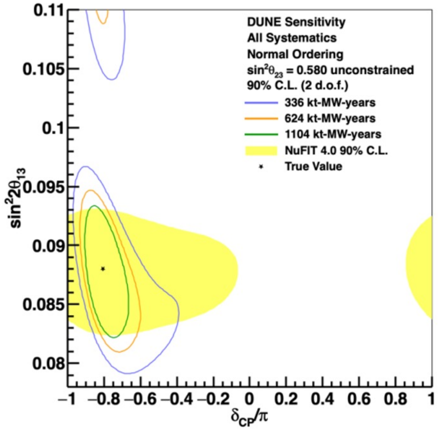
Major Project: DUNE





Neutrinos beamed through the earth from Fermilab (Chicago) to Homestake mine (South Dakota); target is liquid argon time projection chambers, with exquisite tracking of the products of neutrino collisions.

- Phase 1, under construction: 20 kiloton liquid argon target, 1.2 MW beam. Will establish which of the neutrinos is heaviest.
- Phase 2, *as recommended by P5*: target -> 30 kt, beam -> 2.1 MW (ACE-MIRT), upgraded near detector. Most precise measurement of the CP phase across a range of possible CP phase space.



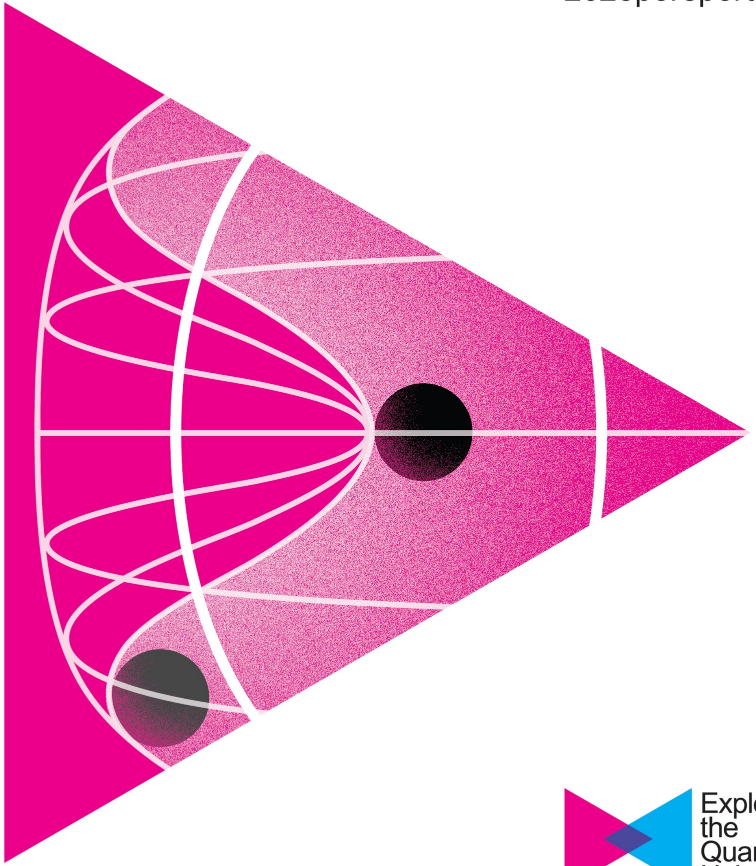
Other Projects

Experiments in progress - long-baseline experiments **NOvA** and **T2K**; the **short baseline program** at Fermilab – should continue. The former in particular provide hints already as to what DUNE may measure; the latter tests DUNE technologies and looks for anomalies.

New agile experiments are encouraged to better understand neutrino-nucleus interactions, to search for unexpected interactions, to better characterize neutrino fluxes from reactors, etc.

DUNE has far detector “modules” which are currently defined as 10 kt liquid argon targets & associated photodetection & readout electronics. The P5 baseline involves 3 modules, but there is space for a fourth. This “**module of opportunity**”, using a different technology, could enable very different physics, and we recommend R&D towards this end

Neutrinos have an effect on cosmological evolution: the sum of the neutrino masses is best constrained from cosmological observations. **Future surveys** will improve these bounds or give information on the neutrino mass scale.



Reveal the Secrets of the Higgs Boson

Exploring the Quantum Universe

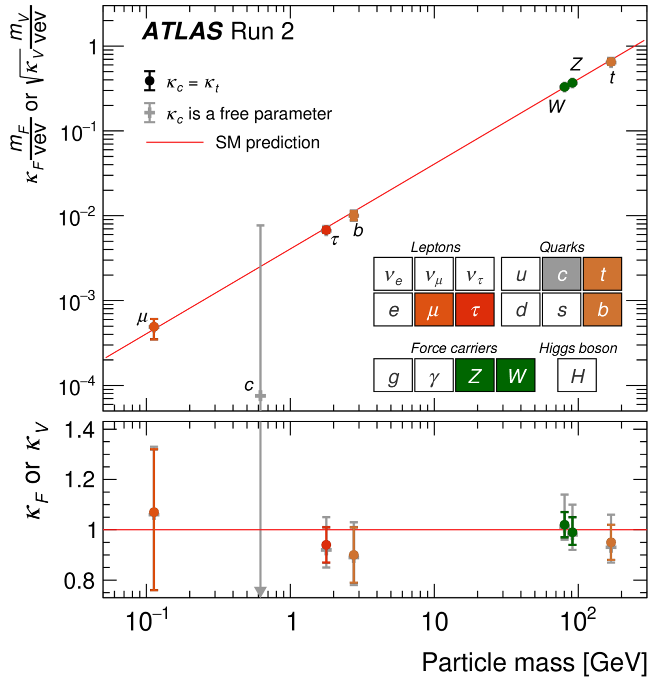
Higgs Boson: At the Center of the Standard Model

The standard model (SM) predicts the Higgs field is connected to mass generation of all fundamental particles
The Higgs field is spin 0, which allows it to have unusual interactions.
The Higgs Boson is an excitation of this field.

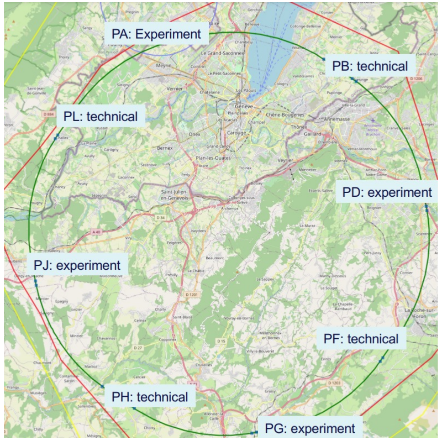
- The SM invokes the simplest possible Higgs field (a fundamental weak doublet).
  - Could the field be **more complicated**?
  - Could it be a condensed **composite** of other, actually fundamental particles?
- The Higgs field **self-interaction** (how it gives itself mass) has not been measured yet.
  - In more complex models than the SM, the related phase transition could drive the creation of the universe's **matter-antimatter asymmetry**.
- By virtue of its quantum numbers and being a scalar, the Higgs could interact with **particles beyond the Standard Model** at tree level (the *Higgs portal*).
  - Any evidence of this?

Higgs at the LHC and beyond

- The Large Hadron Collider (LHC) discovered the Higgs boson, and is also a spectacular place to study its properties.
- New facilities must improve Higgs measurements beyond the High Luminosity LHC (HL-LHC) upgrade *(recommended by P5)*.
- They must also be able to measure the Higgs self-interaction which may link to the matter-antimatter asymmetry in the early universe.



Major Project: Higgs Factory



Define a "Higgs Factory" as an **electron-positron collider** that can cover the range of collision energy **90 GeV** (Z production) to **350 GeV** (top quark pair production)

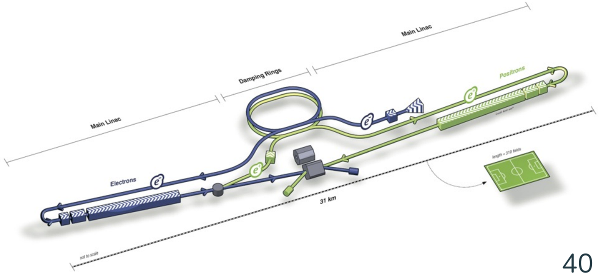
- Very clean environment, with a potential for an **order of magnitude improvement** in important Higgs boson measurements over LHC
- Permits **model-independent measurements** not possible at the LHC
- Depending on models, Higgs measurements sensitive to new physics at up to 10 TeV scale

These are large devices:

- **Circular collider** needs to be very big due to electron synchrotron radiation as they are accelerated (for FCC-ee this is 91 km in circumference)
- Long **linear collider** required, since the electrons are accelerated in one shot (ILC design requires about 20 km in length)

P5 recommends a Higgs Factory, to be built outside the US.

The specific design is to be chosen later this decade.

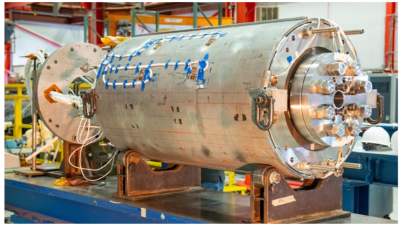


Long Term R&D: 10 TeV pCM Collider

Precision measurement of the shape of the Higgs potential requires collision energies at approximately an order of magnitude beyond LHC.

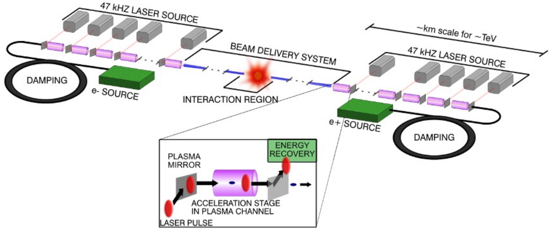
Since protons are not fundamental (the LHC really collides quarks and gluons, at an effective energy of approximately 1 TeV), a collider of electrons or muons reaches the same effective “parton” collision energy with much lower overall energy - 10 TeV vs 100 TeV - thus a smaller machine.

Long Term R&D: 10 TeV pCM Collider

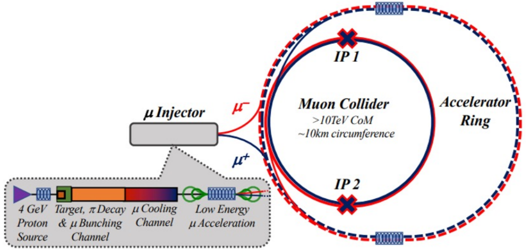


Reaching 10 TeV pCM is a technical and budgetary challenge

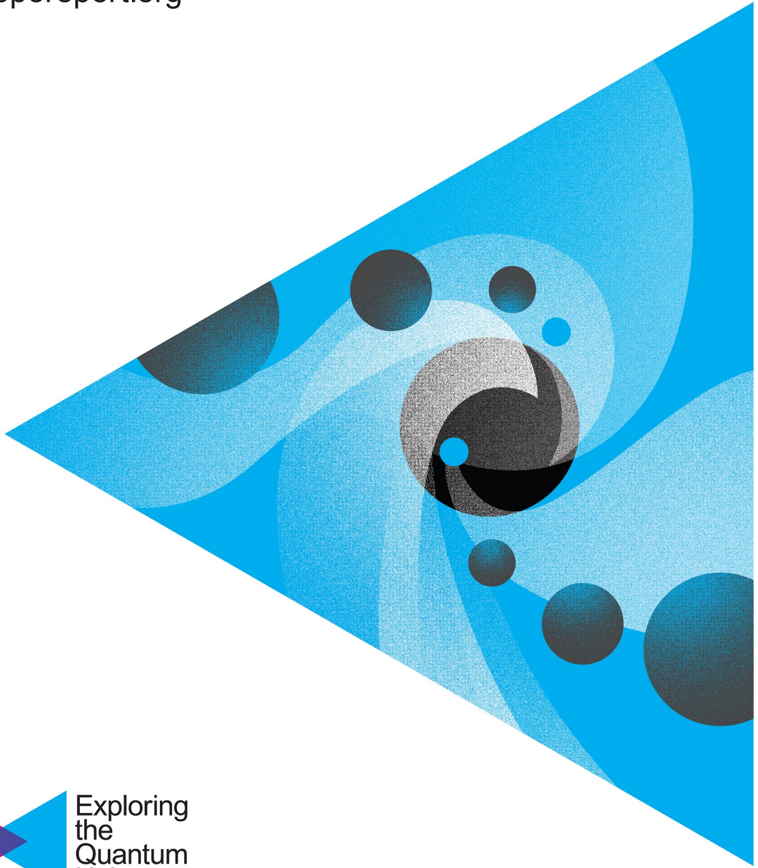
- protons: reuse e.g. 91 km FCC-ee ring, but still need (*many*) high field magnets that don't exist yet
- electrons: standard acceleration technologies would require an accelerator of hundreds of km. Wakefield technologies may be transformative.
- muons: unstable, half life 2.2 μs - need to produce, trap, condense, accelerate them incredibly quickly. But collider ring could be approximately 10 km!



P5 recommends R&D towards all these possibilities.



Need for powerful accelerators cuts across drivers



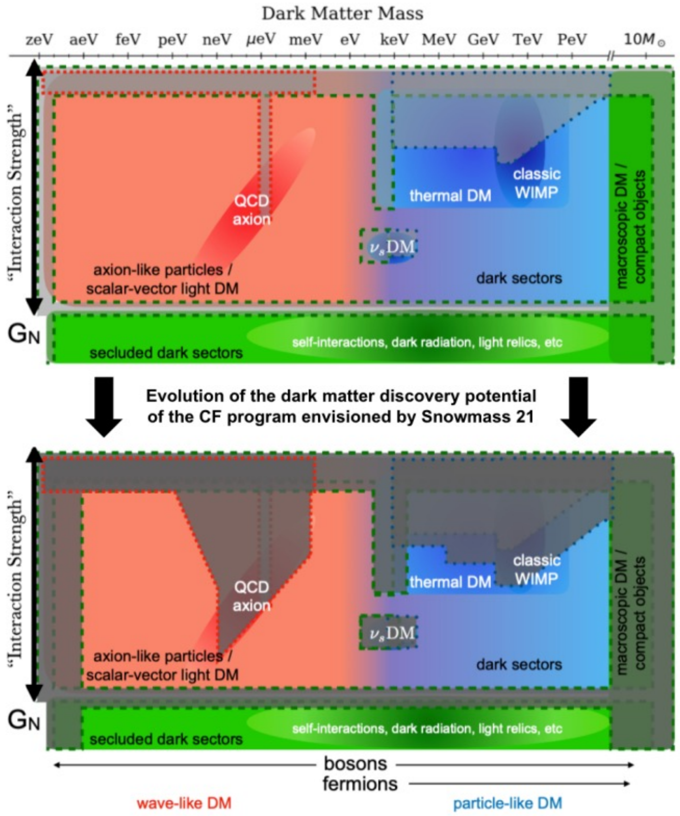
Determine the Nature of Dark Matter

Exploring the Quantum Universe

Dark Matter: the Cosmic Scaffold

The existence of invisible, non-Standard Model matter in the universe is known from its gravitational effects, both now and in the evolution of the universe. There's five times more of it than our kind of matter. But we *really* are clueless about its nature.

- Just what is this stuff? Is it composed of particles in an extension of the Standard Model? Is it a "dark sector" parallel to the Standard Model? Is it black holes?
- Does it interact with itself? Does it interact with Standard Model particles? Perhaps there are other dark particles that interact with the SM?



Ongoing Projects

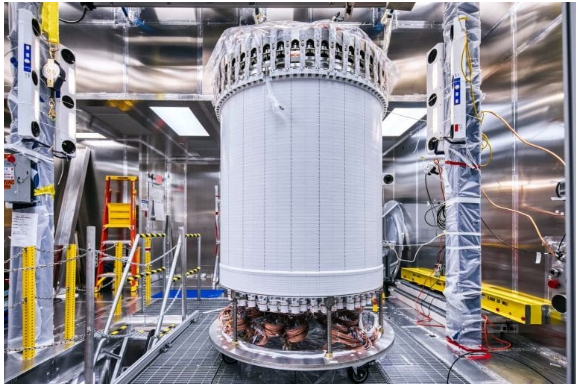
"Second Generation" direct detection experiments

- nuclear recoils in noble liquid detectors (xenon and argon) and nuclear/electron/phonon recoils in semiconductors
- axion -> photon conversion in magnetic fields

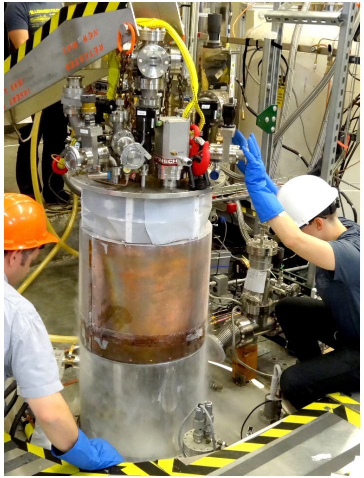
Smaller experiments with other targets (CCDs, bubble chambers, scintillator crystals)

Indirect detection through dark matter annihilation/decay in astrophysical sources, detected through cosmic rays

LZ



ADMX



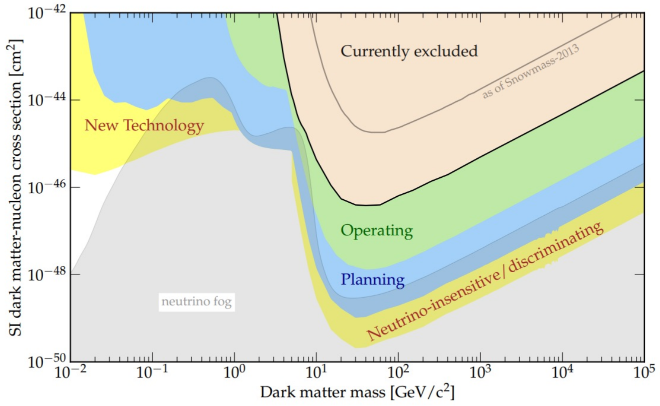
Major Project: Third Generation Direct Detection Experiment

WIMP dark matter is still an extremely important target.

The scalable detection technology is liquid noble gas time projection chambers, using xenon or argon, situated in underground facilities.

With the "G3" experiments we aim to further improve sensitivity until neutrino backgrounds are important (neutrino *floor* or *fog*).

P5 recommends US participation in a G3 dark matter experiment, preferably sited in the US *(at Sanford Lab, the same location as DUNE).*



Mid-scale Projects

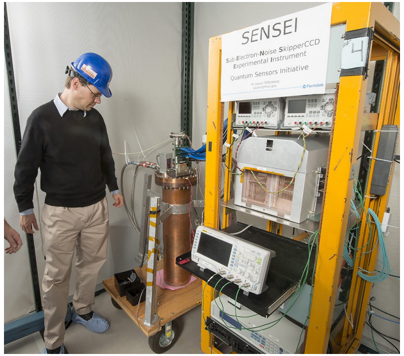
Very broad range of parameter space when moving beyond the WIMP paradigm, much of it only barely touched. Significant progress can come from tabletop experiments.

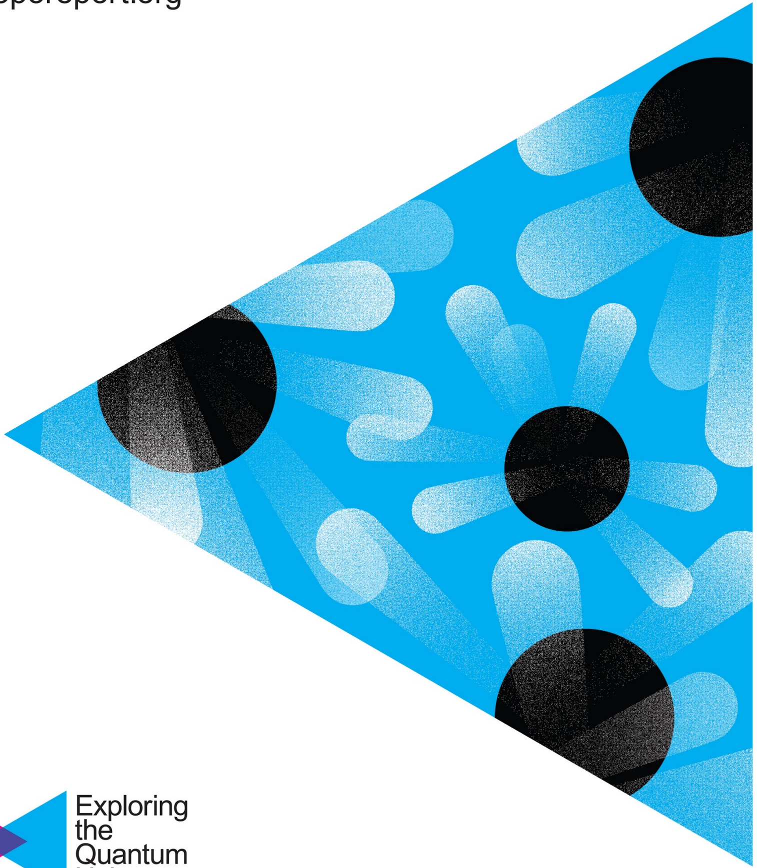
Specific motivation to look for “axions” to understand why there is no neutron electric dipole moment, but want to search broad range.

Includes dark matter particles so light that they act like coherent waves.

Attempt to indirectly detect dark matter through astroparticle signatures: neutrinos from decaying heavy DM (IceCube-Gen2) or cosmic rays from dark matter self-annihilation (Cherenkov Telescope Array, Southern Wide-Field Gamma-Ray Observatory).

***P5 recommends a significant investment in an “agile” portfolio** (including but not limited to dark matter searches).*





Understand What Drives Cosmic Evolution

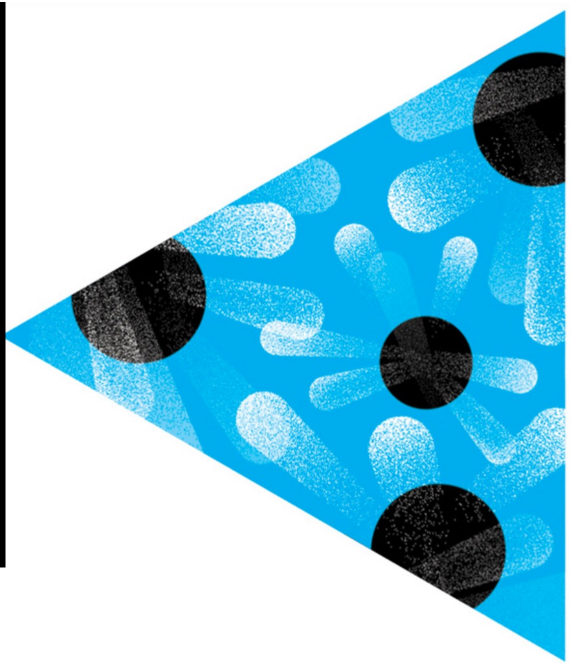
Understand What Drives Cosmic Evolution

The dynamical evolution of the universe is deeply connected to its energy content.

What physics is responsible for the rapid, accelerated expansion during the early inflationary era?

Were there extra light species beyond photons and neutrinos present in the universe during the radiation-dominated era?

What is driving the current accelerated expansion of the universe? We must investigate the nature of dark energy in the ΛCDM paradigm.

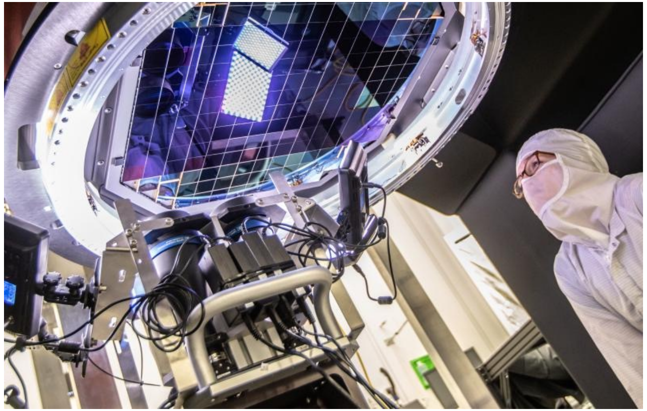


Ongoing Project: Rubin-DESC

The Dark Energy Science Collaboration is one of the groups studying data from the Rubin Observatory's Legacy Survey of Space and Time (LSST).

- Telescope will image entire sky every few nights

Dark energy science: gravitational lensing, galaxy clustering, and type 1a supernovae to map cosmic acceleration

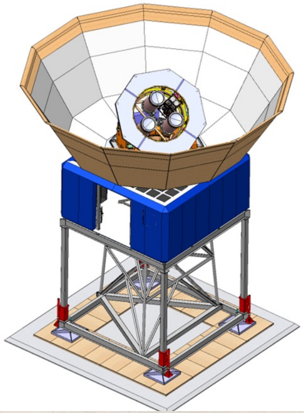


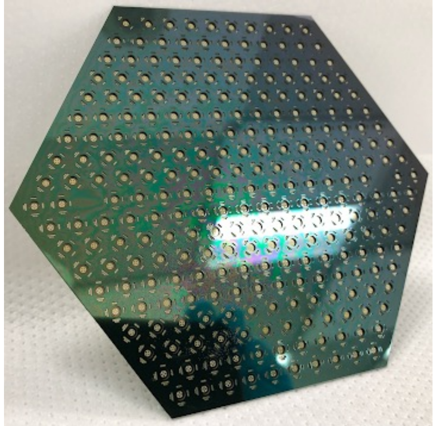
Major Project: CMB-S4

This is a "Stage 4" experiment to precisely measure the features of the cosmic microwave background. Involves telescopes at the South Pole and in Chile making extremely precise measurements of the CMB at many frequencies.

Follows ongoing ground-based program of South Pole Observatory and Simons Observatory

- CMB-S4 will start to be sensitive to **primordial gravitational waves** produced during inflation, in an important class of models.
- It is also sensitive to **dark radiation** - unknown relativistic particles produced in the early universe.
- The gravitational lensing of the CMB by foreground matter will give information on dark matter and energy.





Achieving its goals requires unique US infrastructure at the South Pole

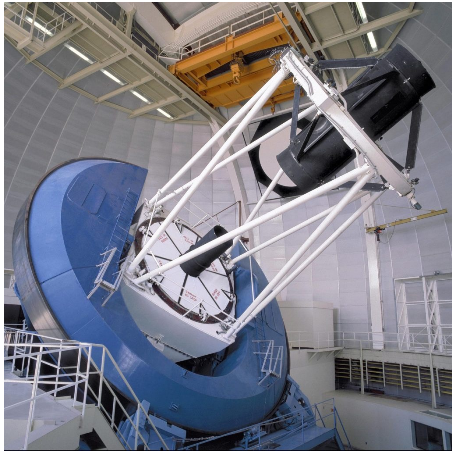
Spectroscopic Surveys

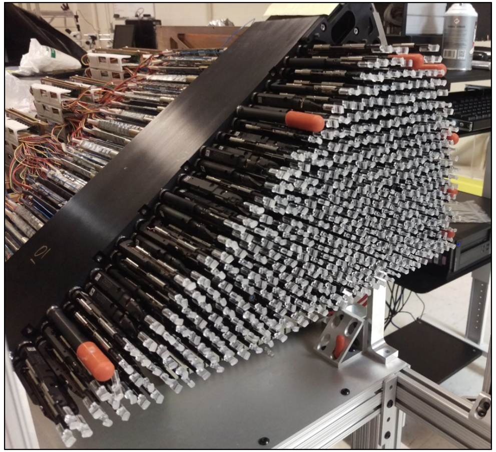
Producing 3D maps of matter distribution in the universe is complementary to studying the cosmic microwave background, e.g. it can probe the evolution of dark energy since the CMB era

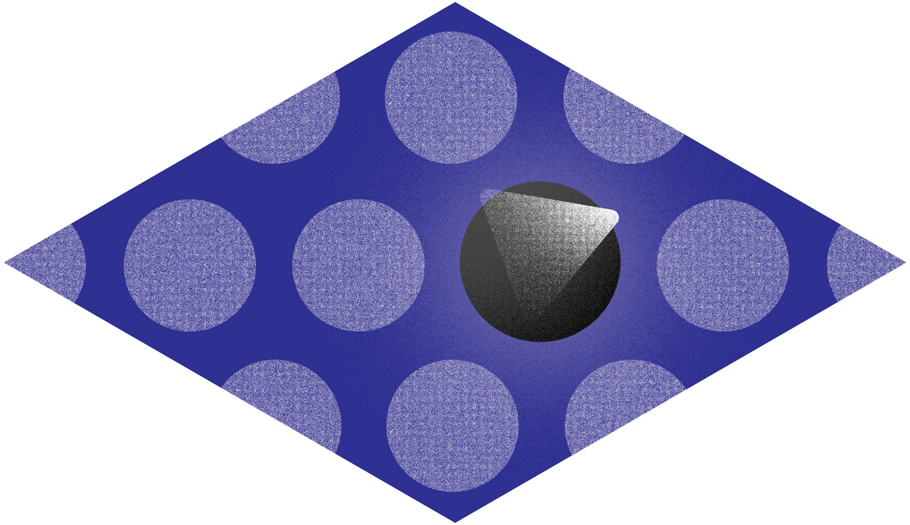
P5 recommends continued operation and upgrade of the DESI spectroscopic survey, which will focus at higher redshift (z > 2)

Also serves as a bridge to the next generation spectroscopic experiments (Spec-S5), demonstrator of certain technologies

Further into the future, the “line intensity mapping” technique may be able to determine mass distributions at different redshifts without resolving the sources explicitly







Search for Direct Evidence of New Particles

Finding New Particles: A Voyage of Discovery

“Who ordered that?” - I.I. Rabi, *on the discovery of the muon*

Experimental particle physics is not just coloring in between the lines of various theoretical models - we need to actually see what the universe has given us.

The most robust technique is to **directly produce new kinds of particles**, either with increasingly energetic accelerators or increasingly intense ones.

Finding New Particles: A Voyage of Discovery

Most current activity is at the Large Hadron Collider (and its upcoming upgrade, High Luminosity LHC).

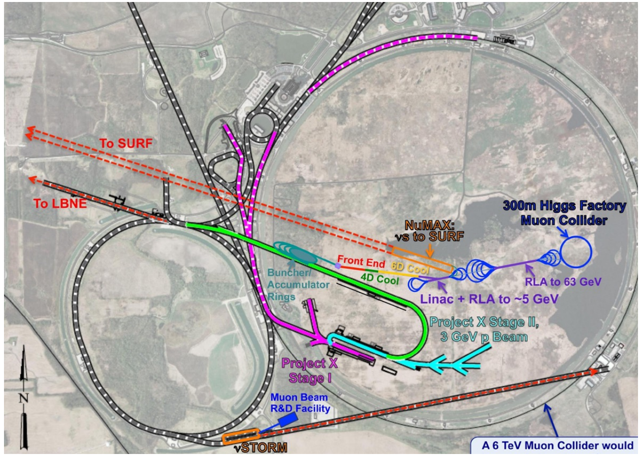
- A question of acute importance given LHC results: are there additional particles that stabilize the mass scale of the Higgs and weak bosons (which should otherwise require extreme fine tuning of parameters before renormalization)?
- In general, what else is out there? Most of the universe isn't Standard Model particles, and the SM can't answer questions like how we wound up with the amount of "normal" matter we have. **There *must* be new physics**.

Opportunities this decade and beyond

Top priority: Complete ongoing ATLAS, CMS, and LHCb experiments.

Next: Both the HL-LHC and a Higgs Factory will expand our reach in directly producing new particles.

Small projects, through ASTAE, could open up exciting possibilities with auxiliary experiments at CERN or using protons from PIP-II at FNAL.

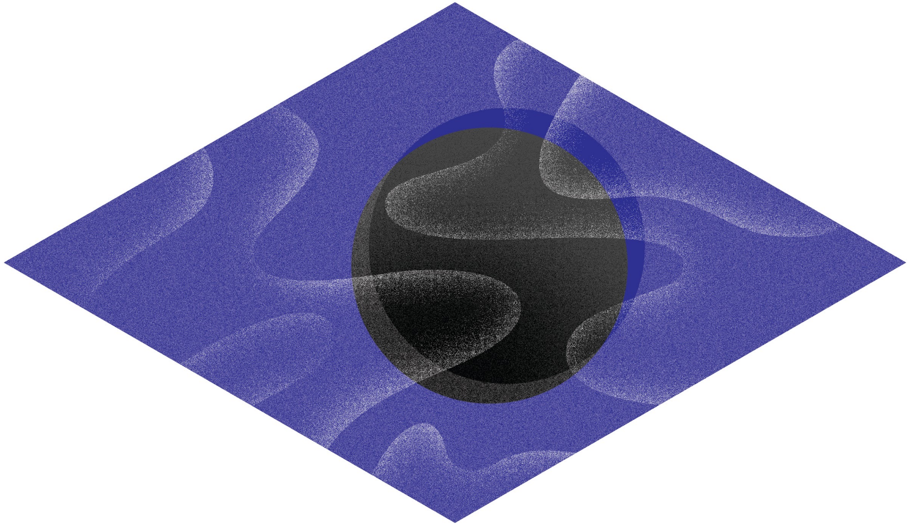


A 10 TeV pCM collider would provide dramatic increases in sensitivity to new particles and could bring energy frontier back to US soil.

Sensitivity for new gauge bosons, fermions, or other resonances will be extended by an order of magnitude beyond the HL-LHC

Access to rare decays and new hidden sectors

Reach the thermal WIMP target for minimal WIMP candidates



Pursue Quantum Imprints of New Phenomena

Exploring the Quantum Universe

Quantum Imprints: Following the Tracks of New Particles

Historically, we have very often found evidence for unknown particles and interactions by comparing careful measurement with theoretical predictions

- beta decay -> weak force
- certain kaon decays are rare -> charm quarks
- matter-antimatter asymmetry in kaons -> bottom and top quarks
- precision top quark and W boson mass measurements -> the Higgs boson couldn't be too heavy

This program can be continued with intense beams and large samples of particles, even without going to the highest possible energies

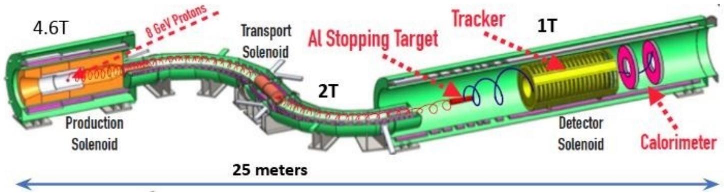
- There are currently some deviations that might be signs of something new:
  - the anomalous magnetic moment of the muon (g-2)
  - the rates of certain bottom quark decays
- Without new physics, the Higgs field appears to be in a metastable state

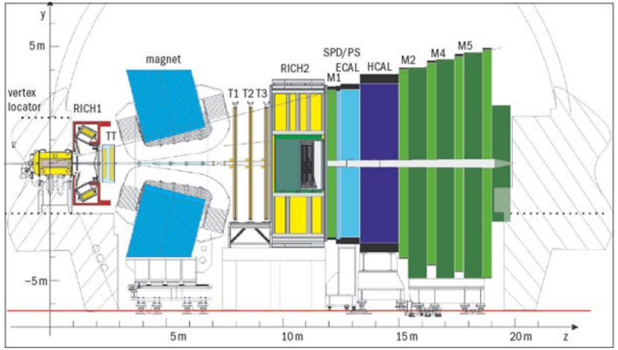
Opportunities this decade and beyond

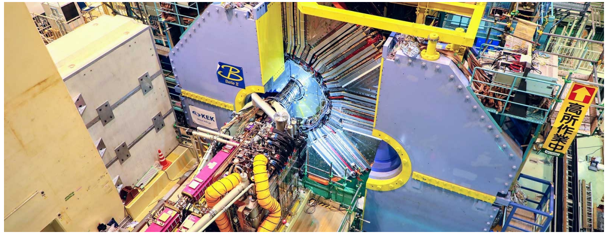
There are ongoing projects focused on quantum imprints: the Mu2e experiment at Fermilab, and LHCb (CERN) and Belle-II (KEK). ***P5 recommends these continue to completion, and recommends US participation in Belle-II upgrades (including the accelerator) and LHCb upgrades***.

The next big opportunity for research in this direction is actually the Higgs Factory. As we defined it, it is an extremely versatile facility:

- In its lower energy range, it will precisely study the behavior of the W and Z bosons, which could reveal more complicated mass generation for them.
- If a circular option is chosen, enough Z bosons can be made that it becomes a competitive source of bottom and charm quarks and tau leptons,
- at the top of the energy range, the top quark mass will be precisely measured.







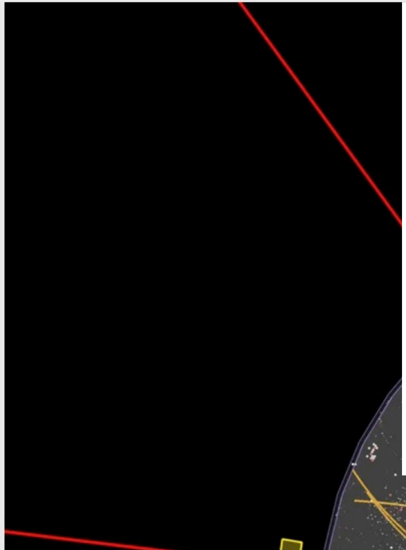
What is next? The muon shot!

AUGUST 28, 2023 | 10 MIN READ

Particle Physicists Dream of a Muon Collider

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists

BY DANIEL GARISTO



TECHNOLOGY NEWS SUBURBAN CHICAGO

Fermilab's 'muon shot' could see suburban lab become site of revolutionary particle collider

An influential panel of the world's top particle physicists is recommending exploring building the most powerful collider on Earth to help unwind the universe's mysteries.

By Mitchell Armentrout | Dec 15, 2023, 4:39pm CST

The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**


SHOOT FOR
THE MUON


SHOOT FOR
THE MUON


BUILD
BUILD

The Humans!

Addressing the profound scientific inquiries within particle physics, from understanding the fundamental building blocks of nature to mapping out the evolution of the universe, requires a creative and technologically advanced workforce operating within an environment of mutual trust. The inherent curiosity driving our exploration of the natural world is a universal aspect of human nature. This shared curiosity serves as the driving force behind our commitment to strengthening and expanding this workforce, prompting us to actively seek talent from all corners of society, regions of the country, and on a global scale.

Related recommendations part of the main recommendations and are expanded on in Chapter 7.

The Humans!

The long-term, highly technological nature of particle physics requires ongoing investment in and support of the workforce, at all career stages. The field can only thrive with high ethical standards and broad community engagement.

- P5 recommends increased support for career paths beyond “faculty” and “permanent lab scientist” – in particular research scientist, hardware and software engineer, and technician positions at universities.
- The funding agencies and laboratories should provide infrastructure to report and resolve violations of ethical conduct, at scales from individual investigators to large formal collaborations.
- Funding should be available for developing partnerships to improve and broaden recruiting, to improve training and mentoring, and to retain personnel with living wages and sufficient support for caregiver and family responsibilities.
- Comprehensive work climate studies should be performed in conjunction with experts in such studies.
- Dissemination of results to the public should be a standard part of operations and research budgets.

Summary

- The Particle Physics Projects Prioritization Panel has reviewed proposals for projects in the next decade and beyond.
- A diverse and balanced range of projects is recommended, both from a physics and project size perspective, considered in a global context.
- Fascinating discoveries will be enabled by the recommended projects.
- The panel made recommendations for improving the health of the field beyond building projects.

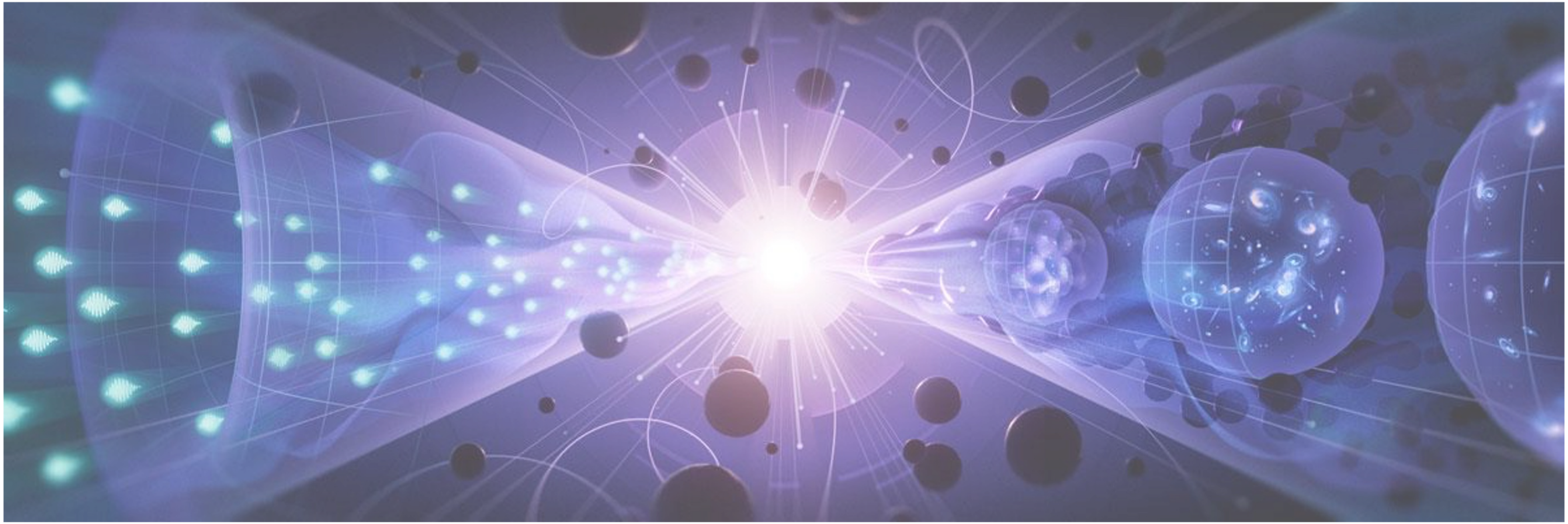
Very exciting times in particle physics!

2023p5report.org


DARK MATTER
QUANTUM
INNOVATION
DISCOVERY


My partner was on P5
and all I got was this T-shirt
and a stressed-out partner

Comments? Questions? Thoughts?

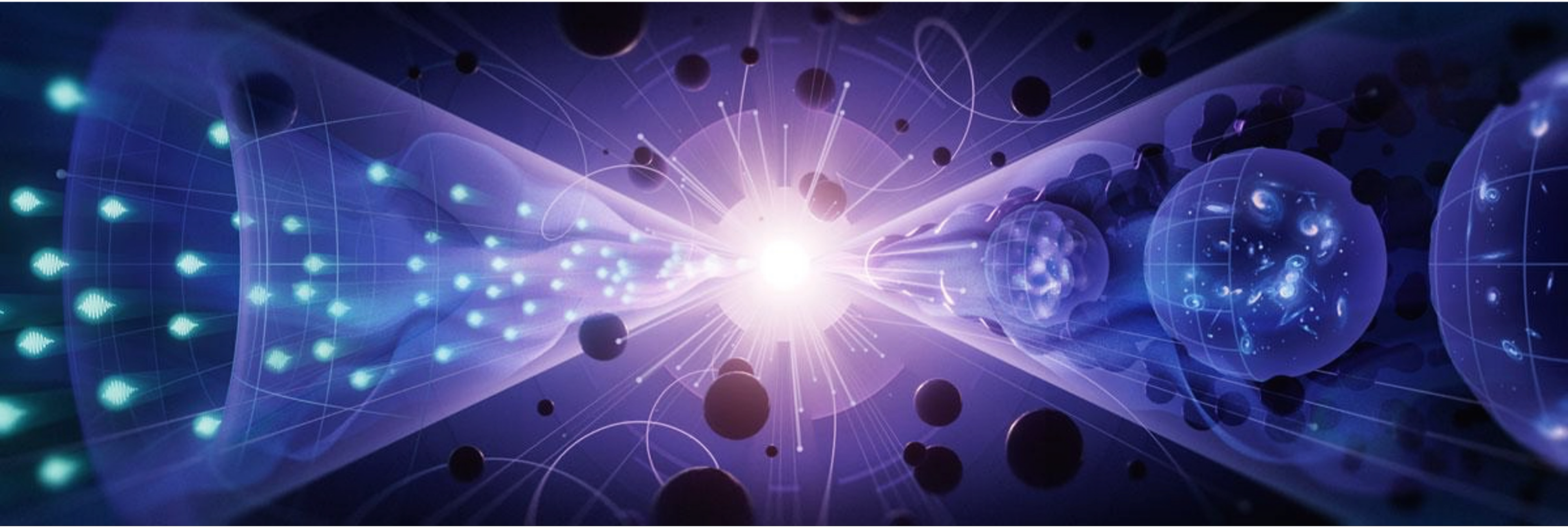


https://www.usparticlephysics.org/2023-p5-report/

Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

https://www.usparticlephysics.org/2023-p5-report/



Please consider endorsing the report: https://forms.gle/63gqBj3vyPn6hwFD9

Experiments at South Pole Station featured prominently in the recent P5 report (https://www.usparticlephysics.org/2023-p5-report/). At the most recent HEPAP meeting (https://science.osti.gov/hep/hepap/Meetings), NSF has announced that refurbishment of South Pole Station will result in a delay of approximately 10 years of these experiments.

Among other issues is the aging C130 fleet needed for logistics. Recently Senators Schumer and Gillibrand have written a letter to the Secretary of the Air Force asking for recapitalization of the LC-130H fleet. More information on the letter can be found at: https://www.gillibrand.senate.gov/news/press/release/schumer-gillibrand-launch-new-push-to-upgrade-crucial-lc-130h-ski-bird-fleet-at-stratton-air-national-guard-base-in-schenectady-county-senators-say-upgrading-the-109th-airlift-wing/

You may wish to encourage your elected officials to support this letter.