Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Mark Palmer, Brookhaven National Laboratory

Presentation to the IMCC Steering Committee

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U.S. DEPARTMENT OF ENERGY

NSF

P5 Panel

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Lindley Winslow (MIT)
Tien-Tien Yu (Oregon)
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Blue: international members

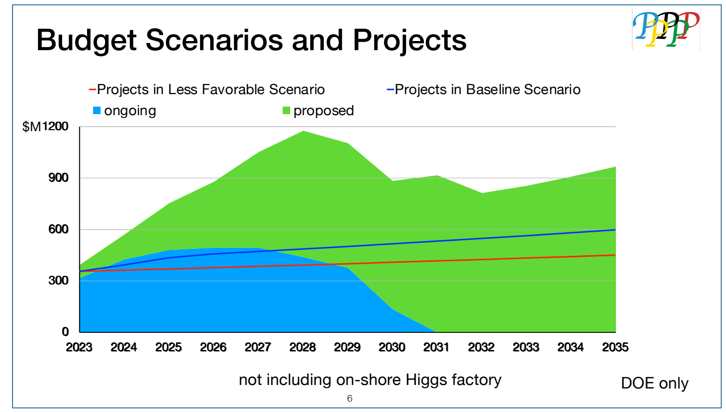

P5 Panel
Smash Particles
Great panel!

1

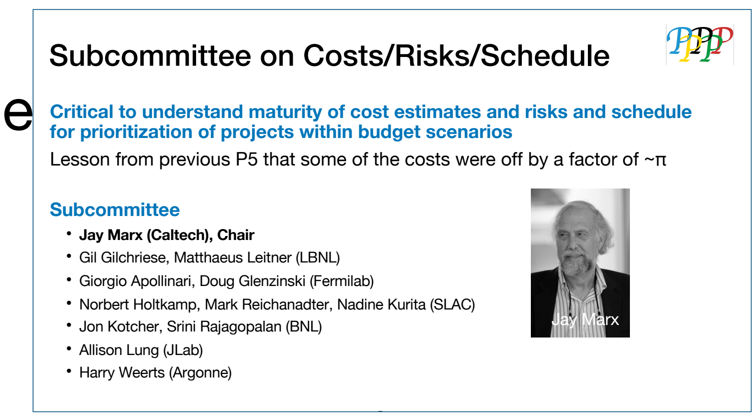
Introduction

A Brief Overview of the Process

- Proposed efforts far exceeded the plausible budget scenarios

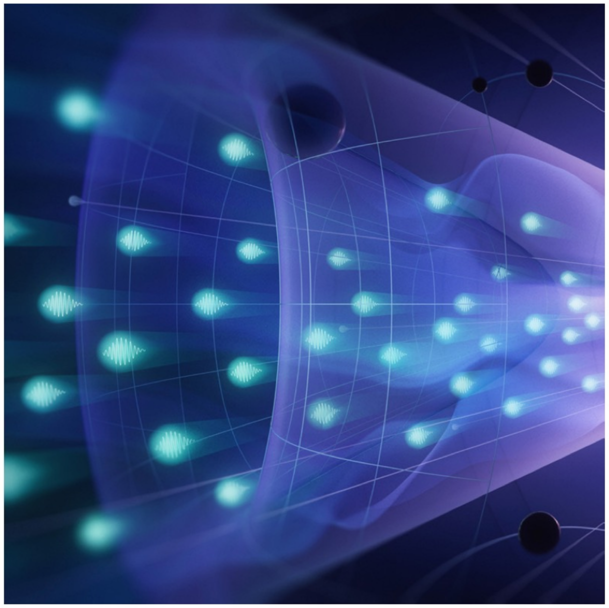


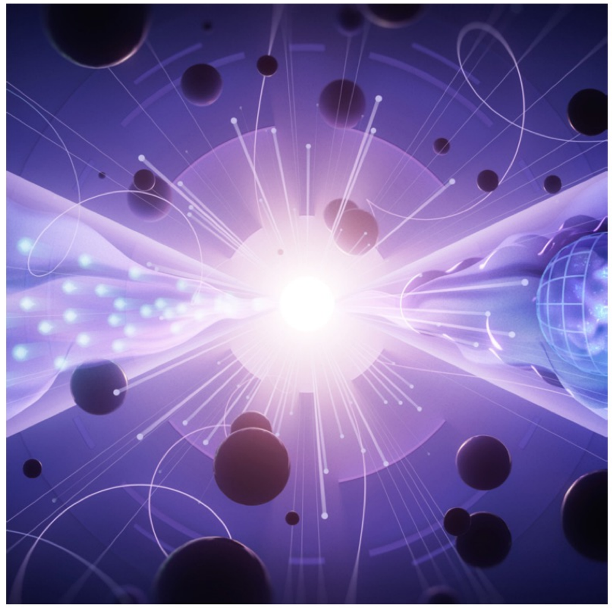
- Critical to carefully evaluate project costs
  - Concerns about potential cost growth
  - Sub-committee on Costs, Risks & Schedule
  - Chaired by Jay Marx

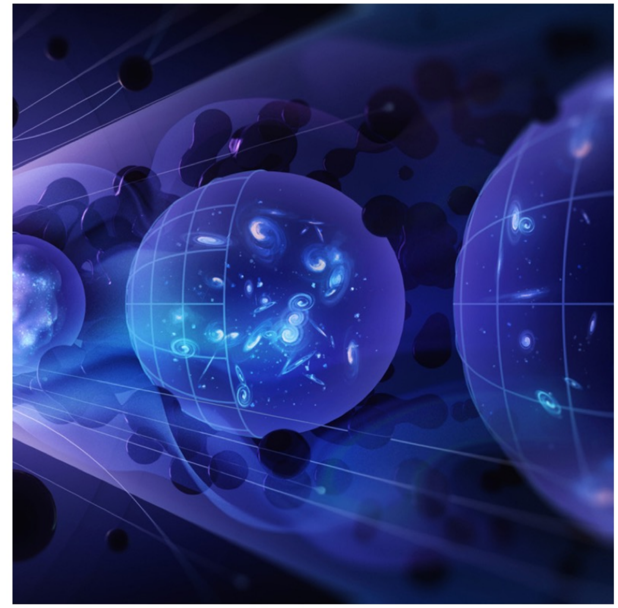


Some Context

- US Budget Cycle:
  - 3-year process
  - Will need until roughly FY26 to fully implement changes
- Present budget
  - Authorization in the CHIPS & Science Act has ***not*** resulted in corresponding budget ***appropriations!***
  - *Significant constraints and likely more limited ramp-up of new initiatives*
- DOE Planning
  - DOE-HEP internal planning process is now underway
  - *Updates to plans expected later in the year*







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

Thrusts tied to Collider Program are highlighted in blue boxes

Prioritization Principles

In the process of prioritization, we considered **scientific opportunities, budgetary realism, and a balanced portfolio** as major decision drivers.

Large projects (>$250M)
- Paradigm-changing discovery potential
- World-leading
- Unique in the world

Medium projects ($50–250M)
- Excellent discovery potential or development of major tools
- World-class
- Competitive

Small projects (<$50M)
- Discovery potential, well-defined measurements, or outstanding technology development
- World-class
- Excellent training grounds

2

The Recommended Particle Physics Program

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2 The Recommended Particle Physics Program

2.1 Overview

A particle physics program that tackles the most important questions in each of the science drivers **maximizes its potential for groundbreaking scientific discovery**. Executing such a program requires a **balanced portfolio of large, medium, and small projects**, coupled with substantial investments in forward-looking R&D and the development of a skilled workforce for the nation.

Building upon the foundations laid by the previous P5, our recommended program completes ongoing projects and capitalizes on their momentum. A suite of new initiatives at a range of scales includes major projects that will shape the scientific landscape over the next two decades. The prioritized time sequencing of recommended projects and R&D, summarized in Figure 1, reflects our current understanding of the scientific landscape and its associated uncertainties.

The overall program is **carefully constructed to be compatible with the baseline budget scenario provided by DOE**. To achieve that, **we recommend continuing specific projects, strategically advancing some to the construction phase, and delaying others**. As shown in Figure 1, in some cases **individual phases or elements of large-scale projects had to be prioritized separately**. The process and criteria by which the recommended initiatives were selected are laid out in section 1.5.

Unfortunately no time to show the whole narrative… I jump to the recommendations

2 The Recommended Particle Physics Program

2.2 Recommendations

To drive US particle physics forward and maintain strong global leadership, we advocate a **comprehensive and balanced program** that strategically addresses the three science themes and their six interwoven drivers. The numerical order of the recommendations listed below is not meant to reflect their relative priority; instead it is used to group them thematically. The lists under the recommendations are not prioritized, except for the list of major projects under Recommendation 2. Each recommendation is stated in boldface, followed by concise, lettered explanations of how the recommendation can be realized. The impact of alternative budget scenarios on the different elements of the program is discussed in section 2.6.

A Full List of Recommendations is provided at the end of the report. That list includes **Area Recommendations** (section 6) in addition to those here.

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Recommendation 1

Not Rank-Ordered

As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. We reaffirm the previous P5 recommendations on major initiatives:

a. **HL-LHC** (including ATLAS and CMS detectors, as well as Accelerator Upgrade Project) to start addressing why the Higgs boson condensed in the universe (reveal the secrets of the Higgs boson, section 3.2), to search for direct evidence for new particles (section 5.1), to pursue quantum imprints of new phenomena (section 5.2), and to determine the nature of dark matter (section 4.1).
b. **The first phase of DUNE and PIP-II** to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science (elucidate the mysteries of neutrinos, section 3.1).
c. **The Vera C. Rubin Observatory** to carry out the LSST, and the LSST Dark Energy Science Collaboration, to understand what drives cosmic evolution (section 4.2).

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Recommendation 1

Not Rank-Ordered

In addition, we recommend continued support for the following ongoing experiments at the medium scale (project costs > $50M for DOE and > $4M for NSF), including completion of construction, operations, and research:

d. **NOvA**, **SBN**, **T2K**, and **IceCube** (*elucidate the mysteries of neutrinos*, section 3.1).
e. **DarkSide-20k**, **LZ**, **SuperCDMS**, and **XENONnT** (*determine the nature of dark matter*, section 4.1).
f. **DESI** (*understand what drives cosmic evolution*, section 4.2).
g. **Belle II**, **LHCb**, and **Mu2e** (*pursue quantum imprints of new phenomena*, section 5.2).

The agencies should work closely with each major project to carefully manage the costs and schedule to ensure that the US program has a broad and balanced portfolio.

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Recommendation 2

Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

These projects have the potential to transcend and transform our current paradigms. They inspire collaboration and international cooperation in advancing the frontiers of human knowledge. Plan and start the following major initiatives **in order of priority from highest to lowest**:

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Rank-Ordered

Recommendation 2

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. **An off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).

Recommendation 2

The prioritization principles behind these recommendations can be found in sections 1.6 and 8.1.

IceCube-Gen2 also has a strong science case in **multi-messenger astrophysics** together with gravitational wave observatories. We recommend that NSF expand its efforts in multi-messenger astrophysics, a unique program in the NSF Division of Physics, with US involvement in the **Cherenkov Telescope Array** (CTA; recommendation 3c), a next-generation gravitational wave observatory, and IceCube-Gen2.

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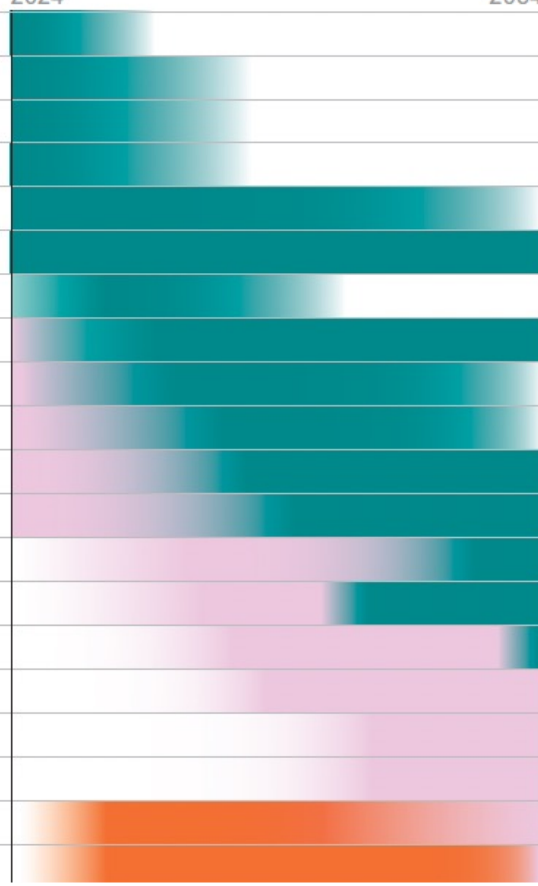
Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation | Construction | R&D, Research | P: Primary | S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

Science Experiments

Timeline 2024 – 2034



Science Experiments	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC		P	P		P	P	
LZ, XENONnT			P				
NOvA/T2K	P				S		
SBN	P				S		
DESI/DESI-II	S		S	P			P
Belle II			S		S	P	
SuperCDMS			P				
Rubin/LSST & DESC	S		S	P			P
Mu2e						P	
DarkSide-20k			P				
HL-LHC		P	P		P	P	
DUNE Phase I	P				S	S	S
CMB-S4	S		S	P			P
CTA			S				P
G3 Dark Matter §	S		P				
IceCube-Gen2	P		S				P
DUNE FD3	P				S	S	S
DUNE MCND	P				S	S	
Higgs factory §		P	S		P	P	
DUNE FD4 §	P				S	S	S

Science Drivers: Neutrinos, Higgs Boson, Dark Matter, Cosmic Evolution, Direct Evidence, Quantum Imprints; Astronomy & Astrophysics

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Recommendation 3

Not Rank-Ordered

Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

In order to achieve this balance across all project sizes we recommend the following:

a. Implement a new small-project portfolio at DOE, **Advancing Science and Technology through Agile Experiments (ASTAE)**, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

b. Continue Mid-Scale Research Infrastructure (**MSRI**) and Major Research Instrumentation (**MRI**) programs as a critical component of the NSF research and project portfolio.

c. Support **DESI-II** for cosmic evolution, **LHCb upgrade II** and **Belle II upgrade** for quantum imprints, and **US contributions to the global CTA Observatory** for dark matter (sections 4.2, 5.2, and 4.1).

The Belle II recommendation includes contributions towards the SuperKEKB accelerator.

Recommendation 4

Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

Investing in the future of the field to fulfill this vision requires the following:

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Recommendation 4

Not Rank-Ordered

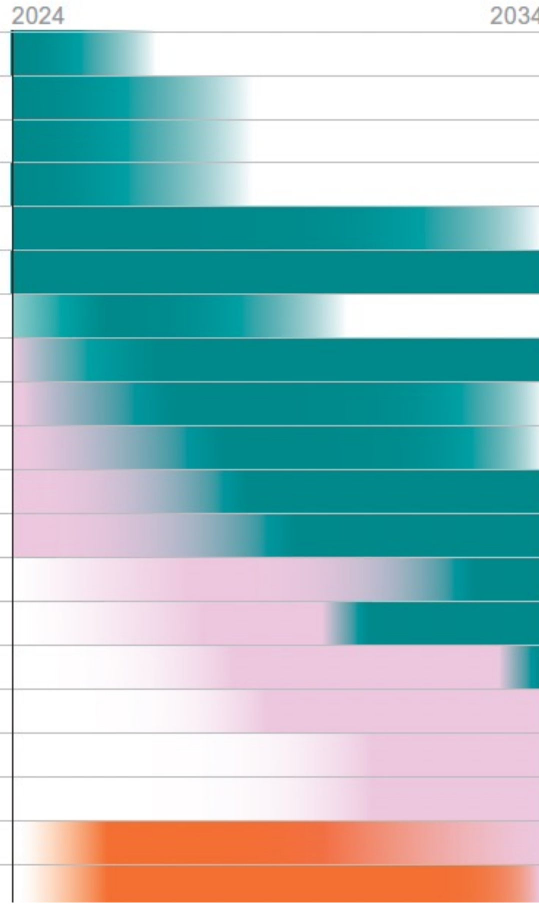
a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).
b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1).
c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).
d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3).
e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).
f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).
g. Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

We recommend specific budget levels for enhanced support of these efforts and their justifications as **Area Recommendations** in section 6.

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation Construction R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations



Science Experiments	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC		P	P		P	P	
LZ, XENONnT			P				
NOvA/T2K	P				S		
SBN	P				S		
DESI/DESI-II	S		S	P			P
Belle II			S		S	P	
SuperCDMS			P				
Rubin/LSST & DESC	S		S	P			P
Mu2e						P	
DarkSide-20k			P				
HL-LHC		P	P		P	P	
DUNE Phase I	P				S	S	S
CMB-S4	S		S	P			P
CTA			S				P
G3 Dark Matter §	S		P				
IceCube-Gen2	P		S				P
DUNE FD3	P				S	S	S
DUNE MCND	P				S	S	
Higgs factory §		P	S		P	P	
DUNE FD4 §	P				S	S	S

Science Drivers: Neutrinos, Higgs Boson, Dark Matter, Cosmic Evolution, Direct Evidence, Quantum Imprints

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation Construction R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

Higgs factory §			P	S		P	P	
DUNE FD4 §		P				S	S	S
Spec-S5 §		S		S	P			P
Mu2e-II							P	
Multi-TeV §	DEMONSTRATOR		P	P		P	S	
LIM		S		P	P			P

Advancing Science and Technology through Agile Experiments

ASTAE §		P	P	P	P	P	P	

Science Enablers

LBNF/PIP-II	
ACE-MIRT	
SURF Expansion	
ACE-BR §, AMF	

Increase in Research and Development

GARD §	TEST FACILITIES
Theory	
Instrumentation	
Computing	

Approximate timeline of the recommended program within the baseline scenario. Projects in each category are in chronological order. For IceCube-Gen2 and CTA, we do not have information on budgetary constraints and hence timelines are only technically limited. The primary/secondary driver designation reflects the panel's understanding of a project's focus, not the relative strength of the science cases. Projects that share a driver, whether primary or secondary, generally address that driver in different and complementary ways.

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Recommendation 5

Invest in initiatives aimed at developing the workforce, broadening engagement, and supporting ethical conduct in the field. This commitment nurtures an advanced technological workforce not only for particle physics, but for the nation as a whole.

Not Rank-Ordered

Recommendation 5

The following workforce initiatives are detailed in section 7:

a. All projects, workshops, conferences, and collaborations must incorporate ethics agreements that detail expectations for professional conduct and establish mechanisms for **transparent reporting, response, and training**. These mechanisms should be supported by laboratory and funding agency infrastructure. The efficacy and coverage of this infrastructure should be reviewed by a HEPAP subpanel.

b. Funding agencies should continue to support programs that **broaden engagement** in particle physics, including strategic academic partnership programs, traineeship programs, and programs in support of dependent care and accessibility. A systematic review of these programs should be used to identify and remove barriers.

c. Comprehensive **work-climate studies** should be conducted with the support of funding agencies. Large collaborations and national laboratories should consistently undertake such studies so that issues can be identified, addressed, and monitored. Professional associations should spearhead field-wide work-climate investigations to ensure that the unique experiences of individuals engaged in smaller collaborations and university settings are effectively captured.

d. Funding agencies should strategically increase support for **research scientists, research hardware and software engineers, technicians, and other professionals** at universities.

e. A plan for **dissemination of scientific results to the public** should be included in the proposed operations and research budgets of experiments. The funding agencies should include funding for the dissemination of results to the public in operation and research budgets.

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Recommendation 6

Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

The panel would consider the following:

1. The level and nature of **US contribution in a specific Higgs factory** including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale **test and demonstrator facilities** in the accelerator and collider R&D portfolios.
3. A plan for the evolution of the **Fermilab accelerator complex** consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

3

Some Key Elements of the P5 Vision

2.3 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.**

2.4 Stewardship of Key Infrastructure and Expertise

Successful completion of the recommended major projects depends on critical US infrastructure (section 6.6), including particular research sites and facilities. **DOE National Laboratories** are critical research infrastructure that must be maintained and enhanced based on the needs of the particle physics community. This is **particularly true for Fermilab** as the only dedicated US laboratory for particle physics. The **South Pole**, a unique site that enables the world-leading science of CMB-S4 and IceCube-Gen2, must be maintained as a premier site of science to allow continued US leadership in these areas. **SURF**, a deep underground research laboratory supported by the South Dakota Science and Technology Authority, private foundation funds, and DOE, is a critical addition to the suite of US research infrastructure, providing new space and essential infrastructure for DUNE and potentially a G3 dark matter experiment.

In other cases, the infrastructure is technological and intellectual. The **GARD** program is critical in supporting a broad range of accelerator science and technology (AS&T) for DOE's Office of Science, separate from the targeted R&D toward future colliders. Along with NSF-funded fundamental accelerator science, GARD supports a broad workforce of essential accelerator expertise. The program also provides stewardship of AS&T for DOE's Office of Science. This program and the balance across the different research thrusts should be reviewed regularly to ensure alignment with the goals in particle physics. Reviews should be conducted by broad teams, not only specialists.

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2.5 International and Inter-Agency Partnerships

In the case of the Higgs factory, crucial decisions must be made in consultation with potential international partners. The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale. The ILC design is technically ready and awaiting a formulation as a global project. **A dedicated panel should review the plan for a specific Higgs factory once it is deemed feasible and well-defined;** evaluate the schedule, budget and risks of US participation; and give recommendations to the US funding agencies later this decade (Recommendation 6). When a clear choice for a specific Higgs factory emerges, US efforts will focus on that project, and R&D related to other Higgs factory projects would ramp down.

Parallel to the R&D for a Higgs factory, **the US R&D effort should develop a 10 TeV pCM collider (design and technology)**, such as a muon collider, a proton collider, or possibly an electron-positron collider based on wakefield technology. The US should participate in the International Muon Collider Collaboration (IMCC) and take a leading role in defining a reference design. We note that there are many synergies between muon and proton colliders, especially in the area of development of high-field magnets. R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating **demonstrator facilities within a 10-year timescale** (Recommendation 6).

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A summary of Area Recommendations as driven by the elements of the preceding slides is included at the end of this talk

Note: Strong support for targeted initiatives in Collider R&D, theory, instrumentation, and computing

These initiatives are not intended to disappear in a less than ideal budget scenario!!!

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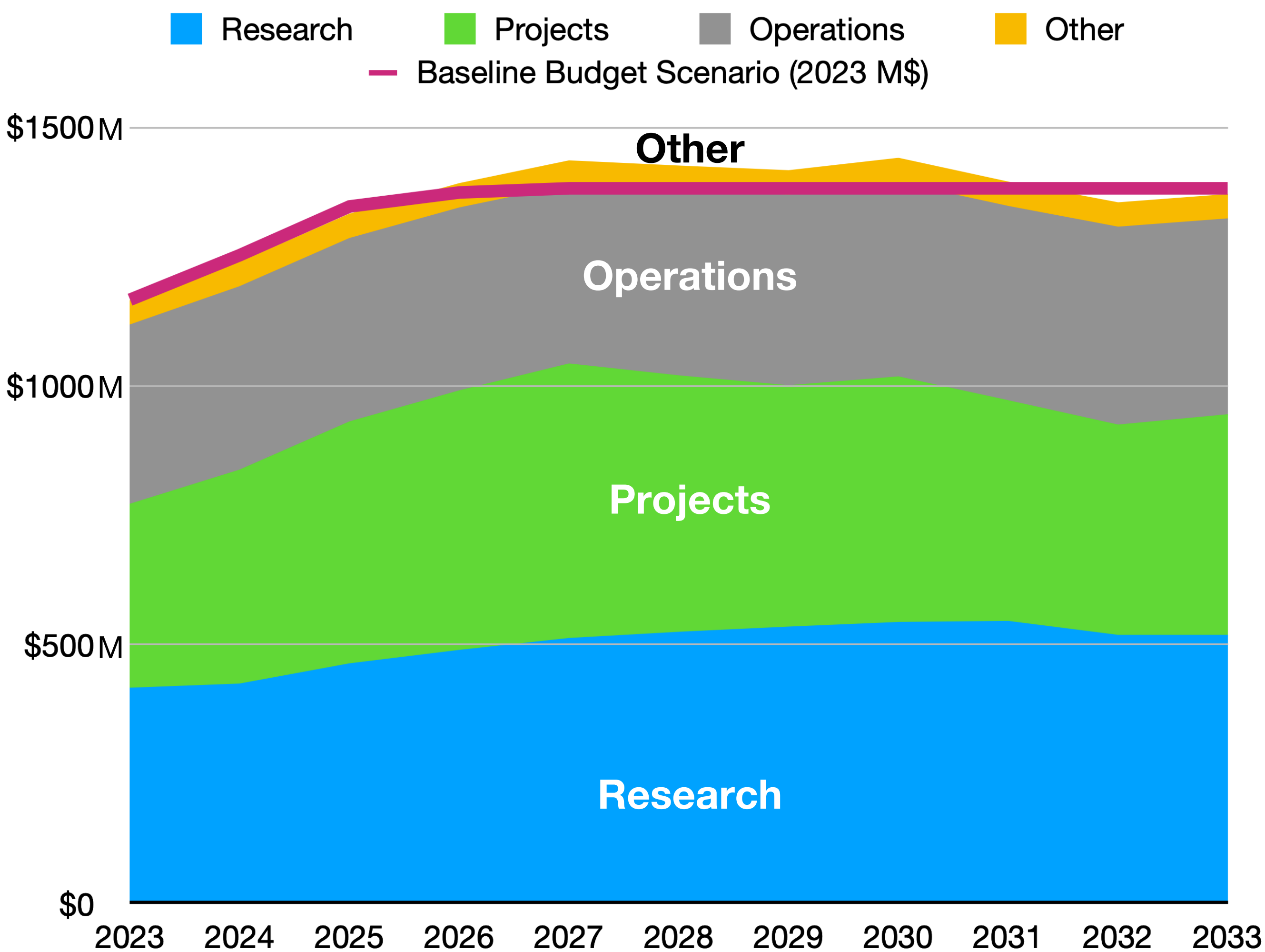

Not in the Report

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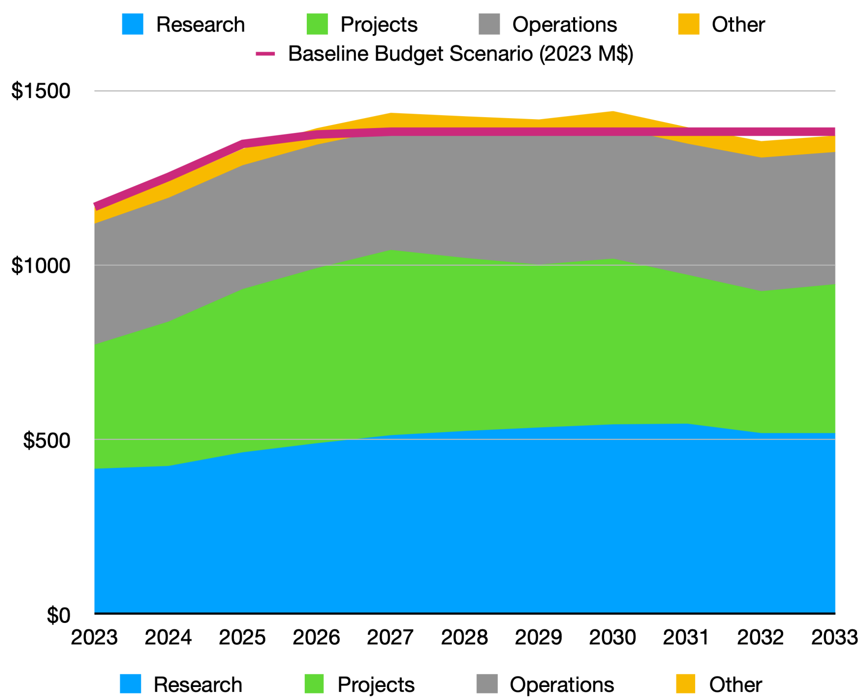
Not in the Report



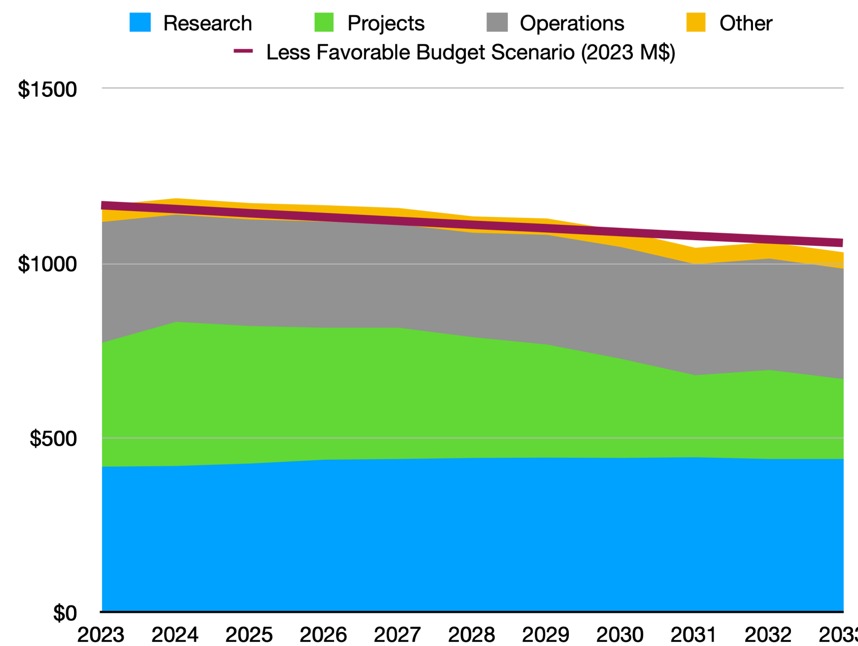


Fig. 2 Evolution of DOE budgets in Research, Projects, Operations, and Other in our budget exercise for the two budget scenarios given in the charge in 2023 dollars assuming 3% annual inflation.

Difficult Choices

Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

A: Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
				Science Drivers						
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	A	A	A			P		P		
FPF #	A	A	A	P		P		P		

Thank you for your attention!

Questions or Comments?

Area Recommendations

Area Recommendations

Theory

1. **Increase DOE HEP-funded university-based theory research by $15 million per year in 2023 dollars (or about 30% of the theory program)**, to propel innovation and ensure international competitiveness. Such an increase would bring theory support back to 2010 levels. Maintain DOE lab-based theory groups as an essential component of the theory community.

ASTAE

2. For the ASTAE program to be agile, we recommend a **broad, predictable, and recurring (preferably annual) call for proposals**. This ensures the flexibility to target emerging opportunities and fields. A program on the scale of **$35 million per year in 2023 dollars** is needed to ensure a healthy pipeline of projects.
3. To preserve the agility of the ASTAE program, **project management** requirements should be outlined for the portfolio and should be adjusted to be commensurate with the scale of the experiment.
4. A successful ASTAE experiment involves 3 phases: **design, construction, and operations**. A design phase proposal should precede a construction proposal, and construction proposals are considered from projects within the group that have successfully completed their design phase.
5. **The DMNI projects** that have successfully completed their design phase and are ready to be reviewed for construction, **should form the first set of construction proposals for ASTAE.** The corresponding design phase call would be **open to proposals from all areas of particle physics.**

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Area Recommendations

Instrumentation

6. **Increase the budget for generic Detector R&D by at least $4 million per year** in 2023 dollars. This should be supplemented by additional funds for the collider R&D program
7. The detector R&D program should continue to leverage national initiatives such as QIS, microelectronics, and AI/ML.

General Accelerator R&D

8. **Increase annual funding to the General Accelerator R&D program by $10M per year** in 2023 dollars to ensure US leadership in key areas.
9. Support generic accelerator R&D with the construction of small scale test facilities. Initiate construction of larger test facilities based on project review, and informed by the collider R&D program.

Collider R&D

10. To enable targeted R&D before specific collider projects are established in the US, an investment in **collider detector R&D funding at the level of $20M per year** and **collider accelerator R&D at the level of $35M per year** in 2023 dollars is warranted.

Exploring the Quantum Universe

Area Recommendations

Facilities and Infrastructure

11. To successfully deliver major initiatives and leading global projects, we recommend that:
    a. National Laboratories and facilities should work with funding agencies to establish and maintain streamlined access policies enabling **efficient remote and on-site collaboration** by international and domestic partners.
    b. National Laboratories should prioritize the **facilitation of procurement processes** and ensure **robust technical support** for experimenters.
    c. National Laboratories and facilities should prioritize the creation and maintenance of a **supportive, inclusive, and welcoming culture**.
12. Form a dedicated task force, to be led by Fermilab with broad community membership. This task force is to be charged with **defining a roadmap for upgrade efforts and delivering a strategic 20-year plan for the Fermilab accelerator complex** within the next five years for consideration (Recommendation 6). Direct task force funding of up to $10M should be provided.
13. Assess the **Booster synchrotron and related systems for reliability risks** through the first decade of DUNE operation, and take measures to **preemptively address these risks**.
14. Maintaining the capabilities of **NSF's infrastructure at the South Pole**, focused on enabling future world-leading scientific discoveries, is essential. We recommend continued direct coordination and planning between NSF-OPP and the CMB-S4 and IceCube-Gen2 projects, which is of critical importance to the field of particle physics.

Exploring the Quantum Universe

Area Recommendations

Software, Computing, and Cyberinfrastructure

16. Resources for national initiatives in **AI/ML, quantum, computing, and microprocessors** should be leveraged and incorporated into research and R&D efforts to maximize the physics reach of the program.
17. Add support for a sustained R&D effort at the level of **$9M per year in 2023 dollars to adapt software and computing systems to emerging hardware,** incorporate other advances in computing technologies, and fund directed efforts to transition those developments into systems used for operations of experiments and facilities.
18. Through targeted investments at the level of **$8M per year in 2023 dollars**, ensure sustained support for key **cyberinfrastructure** components. This includes widely-used software packages, simulation tools, information resources such as the Particle Data Group and INSPIRE, as well as the shared infrastructure for preservation, dissemination, and analysis of the unique data collected by various experiments and surveys in order to realize their full scientific impact.
19. **Research software engineers and other professionals at universities and labs** are key to realizing the vision of the field and are critical for maintaining a technologically advanced workforce. We recommend that the funding agencies embrace these roles as a critical component of the workforce when investing in software, computing, and cyberinfrastructure.

Sustainability

20. HEPAP, potentially in collaboration with international partners, should conduct a dedicated study aiming at **developing a sustainability strategy for particle physics.**

Backup Slides

Exploring the Quantum Universe

Not in the Report

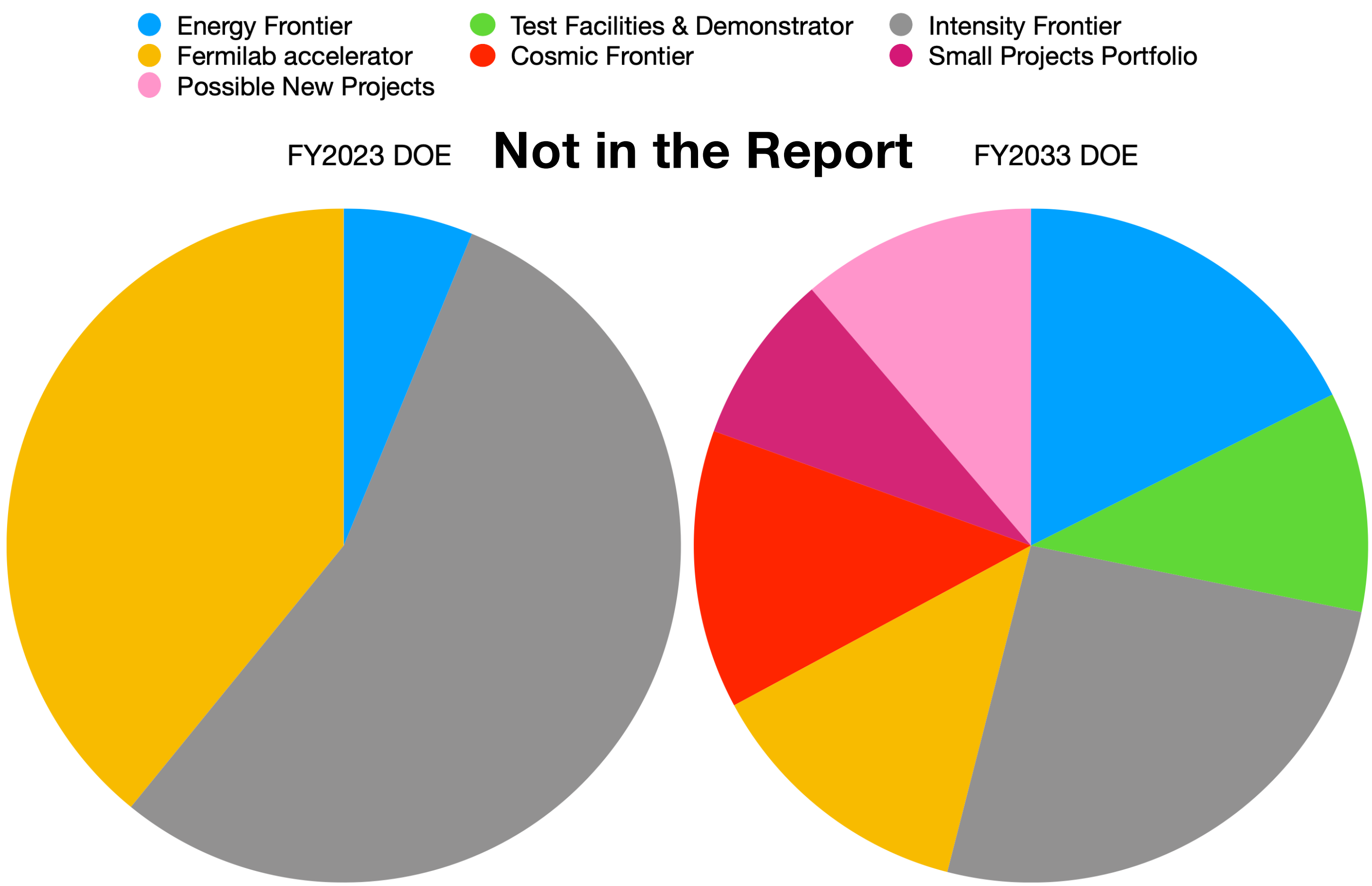

Fig. 3 Composition of DOE Projects in FY2023 (enacted) and FY2033 (recommended) in in our budget exercise. Demonstrator and Small Projects Portfolio are regarded as Projects for this pie chart.

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P5 town hall at FNAL