International MUON Collider Collaboration

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

The P5 Report & Muon Collider Development in the US

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March 9, 2024

@BrookhavenLab

Hokkaido Workshop on Particle Physics at Crossroads

Acknowledgements

US Muon Accelerator Program (MAP)

International Design Study for a Neutrino Factory (IDS-NF)

International Muon Ionization Cooling Experiment (MICE)

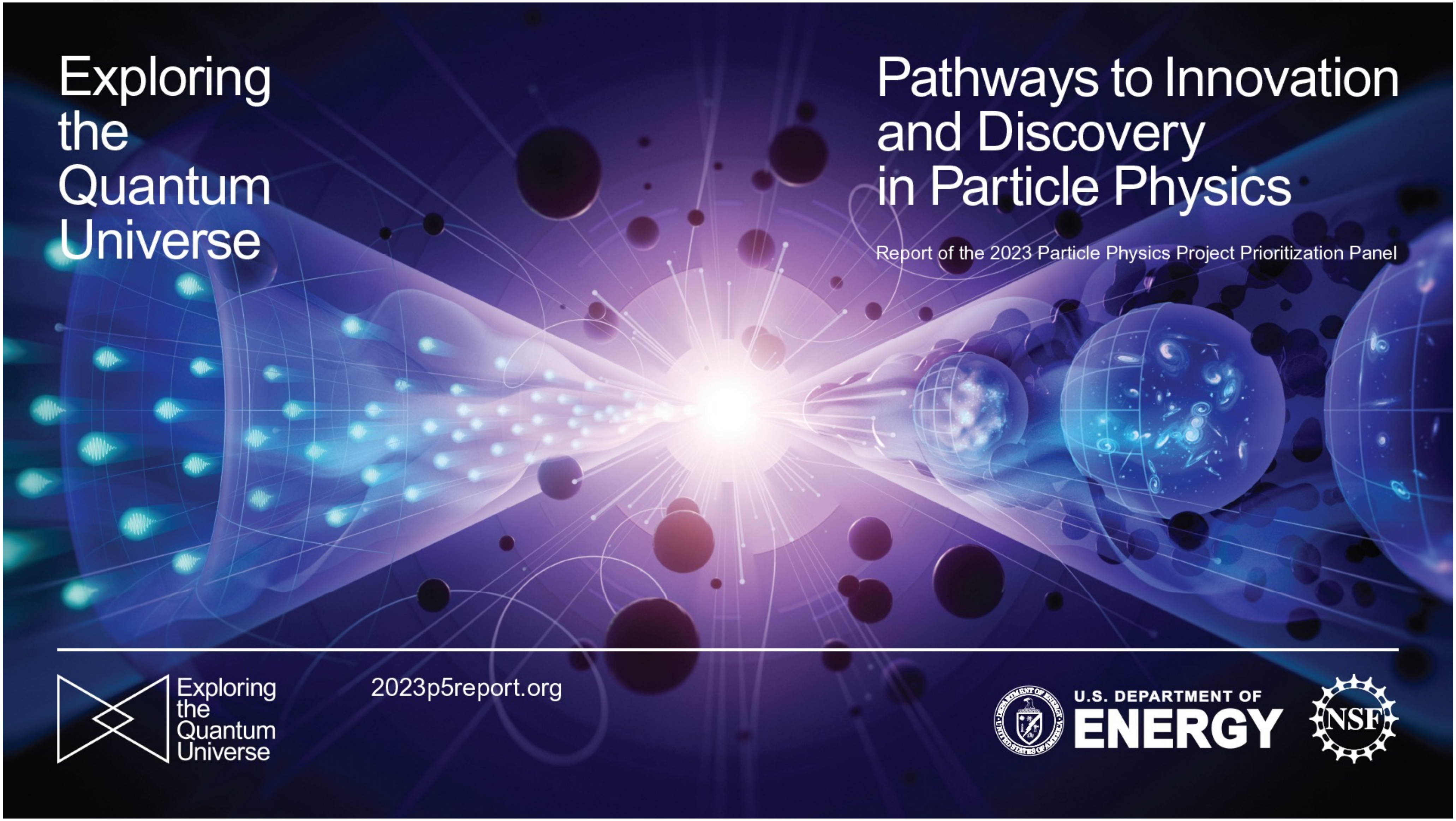
International Muon Collider Collaboration (IMCC)

Snowmass Multi-TeV Collider Topical Group & Contributors

European Laboratory Directors Group – Accelerator R&D Roadmap

Snowmass Muon Collider Forum

2023 Particle Physics Project Prioritization Panel (P5)



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

U.S. DEPARTMENT OF ENERGY

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P5 Panel

Shoji Asai (University of Tokyo)
Amalia Ballarino (CERN)
Tulika Bose (Wisconsin–Madison)
Kyle Cranmer (Wisconsin–Madison)
Francis-Yan Cyr-Racine (New Mexico)
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Cameron Geddes (LBNL)
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Beate Heinemann (DESY)
JoAnne Hewett (SLAC) - HEPAP chair, ex officio until May 2023
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Tor Raubenheimer (SLAC/Stanford)
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Sally Seidel (New Mexico) – interim HEPAP chair, ex officio since June 2023
Seon-Hee Seo (IBS Center for Underground Physics until Sep, Fermilab since Sep)
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Christos Touramanis (Liverpool)
Abigail Vieregg (Chicago)
Amanda Weinstein (Iowa State)
Lindley Winslow (MIT)
Tien-Tien Yu (Oregon)
Robert Zwaska (Fermilab)

Blue: international members


P5 Panel
Great panel!
Smash Particles

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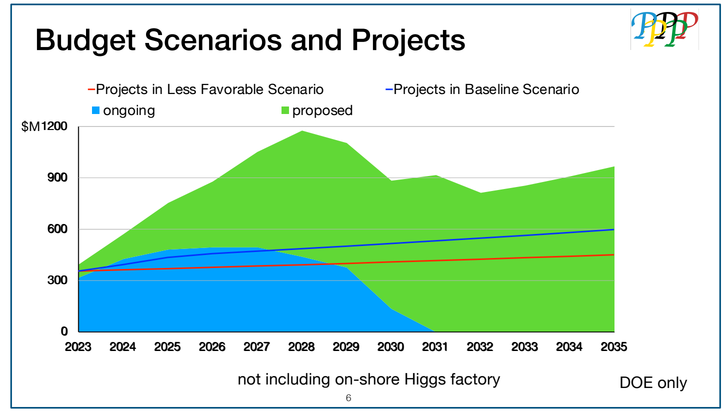
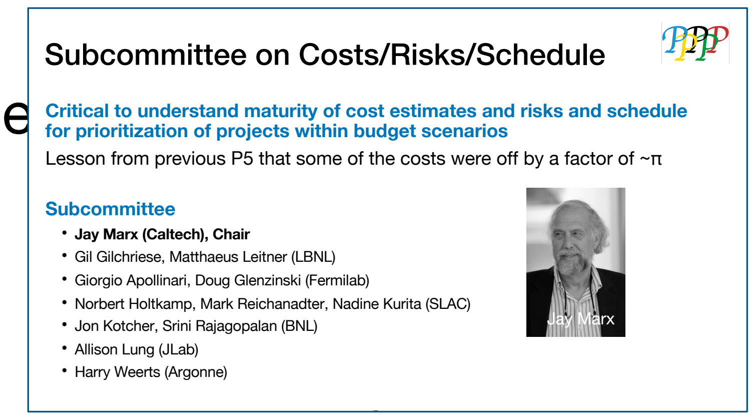
A Brief Overview of the Process

- 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



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A Brief Overview of the Process

Goals and Prioritization Principles:

Overall program should **enable US leadership in core areas of particle physics**

It should leverage **unique US facilities and capabilities**

Engage with **core national initiatives** to develop key technologies,

Develop a **skilled workforce** for the future that draws on US talent

Effective **engagement and leadership in international endeavors** were also considerations

We also **considered the uncertainties in the costs, risks, and schedule** as part of our prioritization exercise. The prioritized project portfolios were chosen to **fit within a few percent of the budget scenarios** and to ensure a reasonable outlook for continuation into the second decade, even though that is beyond the purview of this panel.

Balance of program in terms of

- Size and time scale of projects
- On-shore vs off-shore
- Project vs Research
- Current vs future investment

2.3 The Path to a 10 TeV pCM

A strong motivator for the work being discussed at this meeting

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.

…

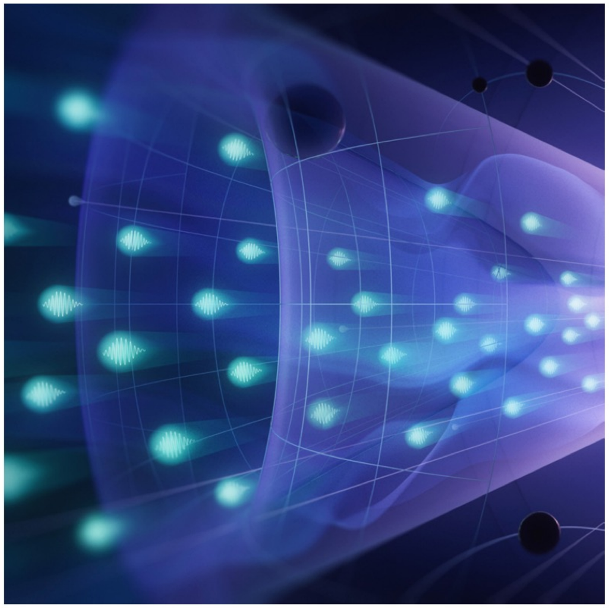
In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt 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.**

1

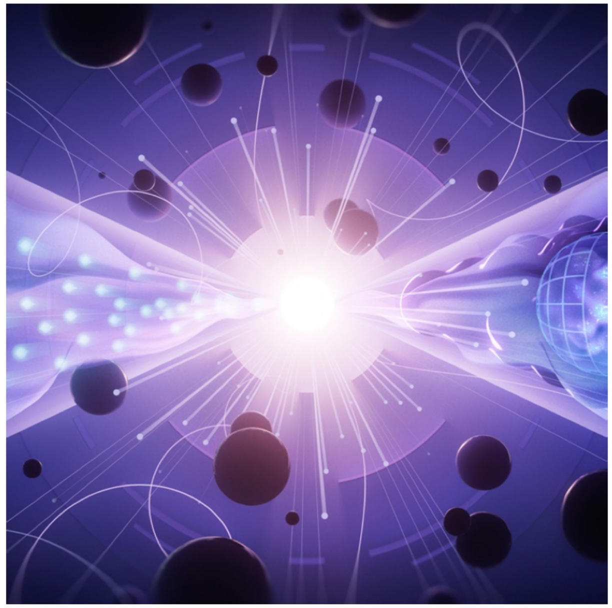
The Science Drivers



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

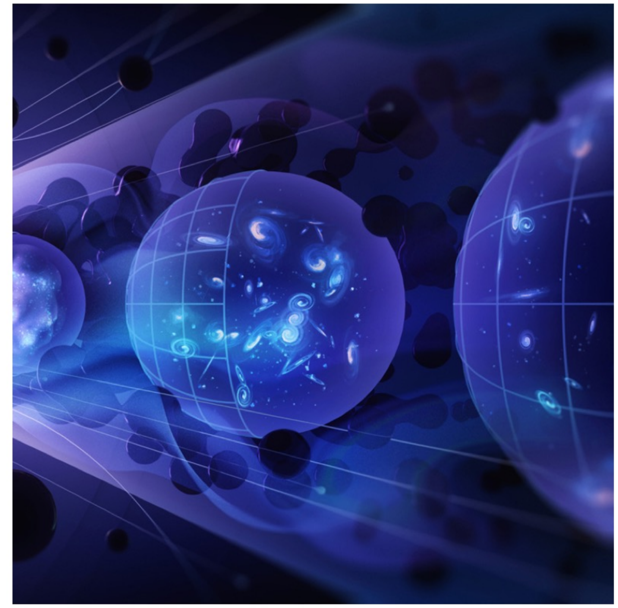
Reveal the Secrets of the Higgs Boson



Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

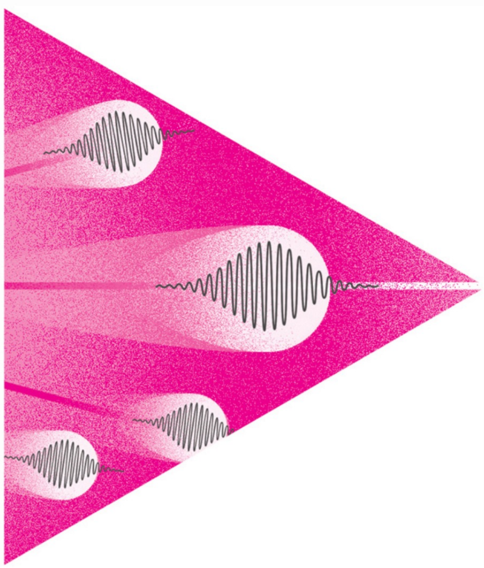


Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Elucidate the Mysteries of Neutrinos

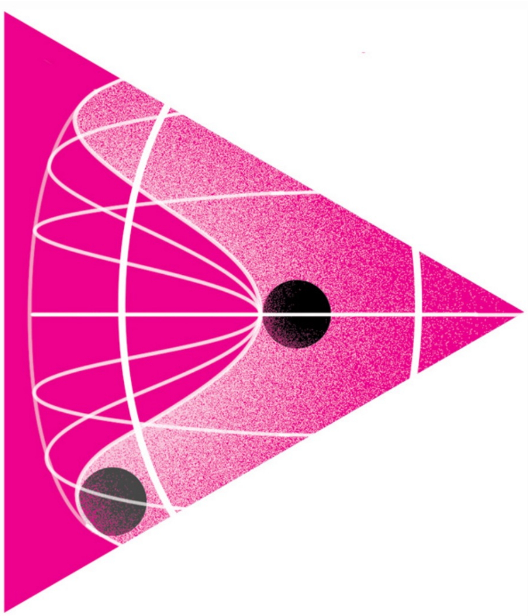


What are the masses of neutrinos?

What is the mass ordering of neutrinos
Are neutrinos their own antiparticles?
Do antineutrinos oscillate differently than neutrinos?
Is CP symmetry violated?
Why do we live in a matter-dominated universe?

What astrophysical phenomena can neutrinos open to us?

Reveal the Secrets of the Higgs Boson



The Higgs is unique. The only fundamental field with a non-zero value in the vacuum state.

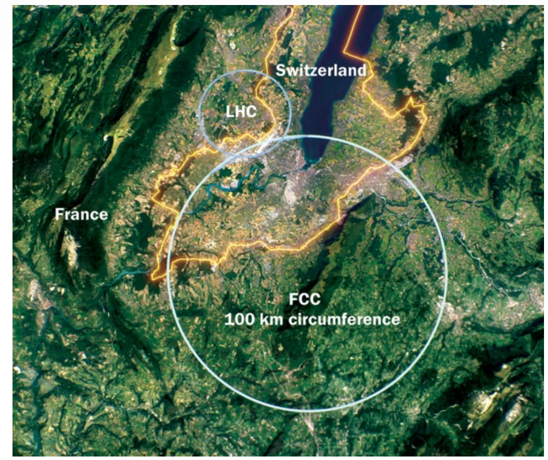
Is the Higgs field fundamental?

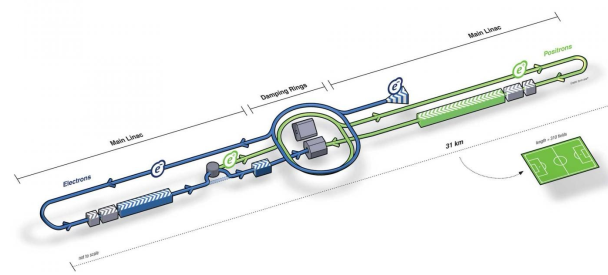
Is there only one, or is there a richer sector with associated particles and new dynamics?

Why is the Higgs mass so low?

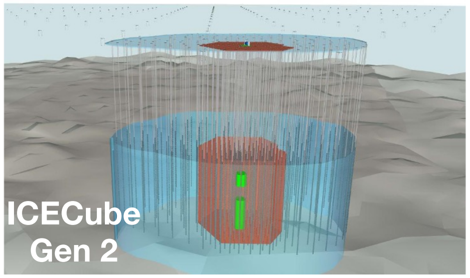
Can the Higgs boson decay to non-Standard Model particles?

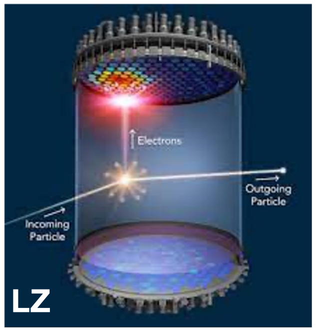
What explains the SM range of coupling strengths to the Higgs?





Determine the Nature of Dark Matter





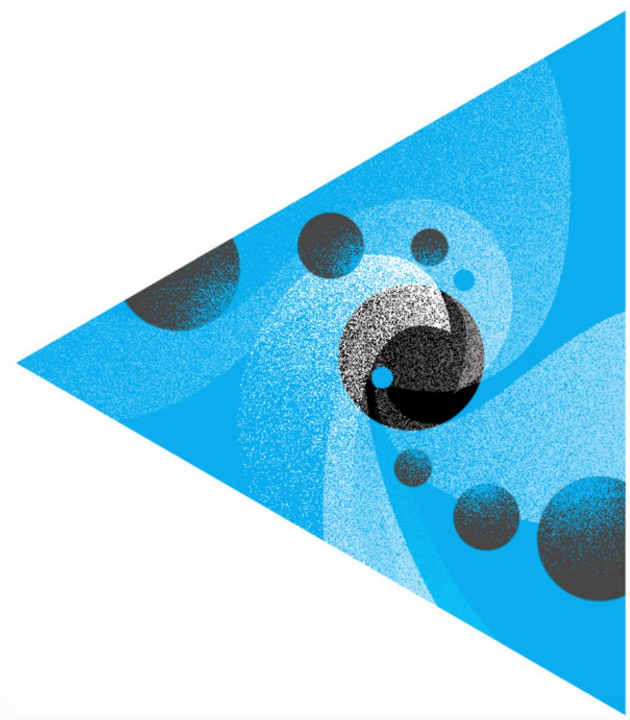
Dark matter comprises most of mass of the universe. How does it interact?

Cosmic Surveys: probe the distribution of dark matter on a variety of length scales

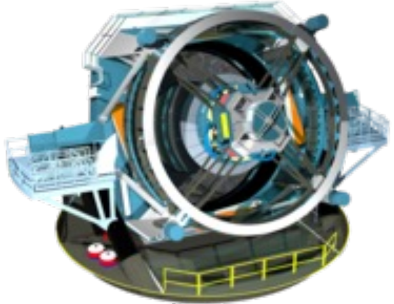
Accelerator-based experiments: attempt to produce dark matter particles

Indirect detection experiments: look for cosmic messengers resulting from dark matter interactions

Direct detection: focus on detecting dark matter's interactions here on Earth



Understand What Drives Cosmic Evolution



Vera Rubin Observatory

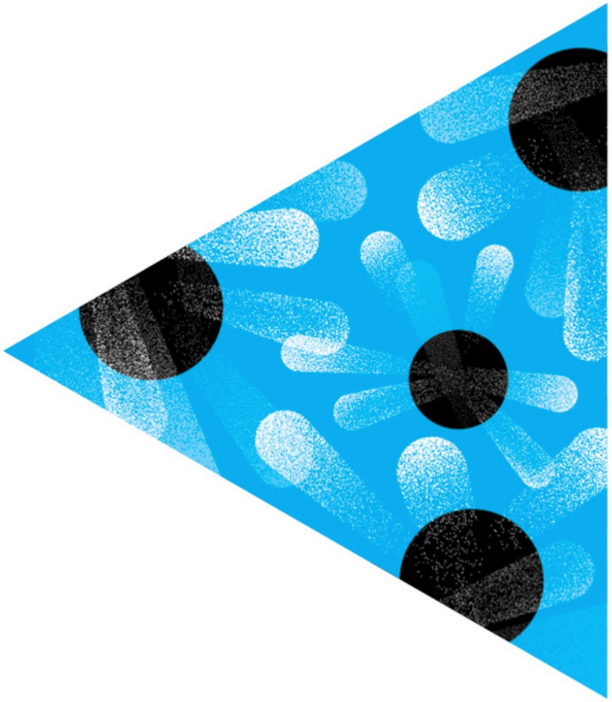
The dynamical evolution of the universe is deeply connected to its energy content.

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

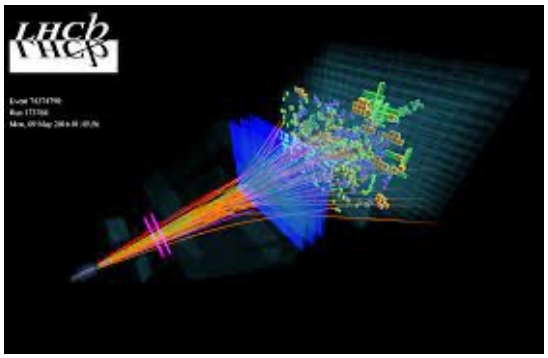
Were extra light species (beyond photons and neutrinos) present in the universe during the radiation-dominated era?

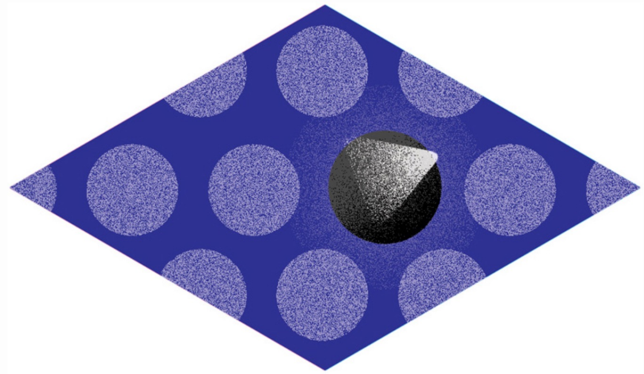
What drives the current accelerated expansion of the universe?

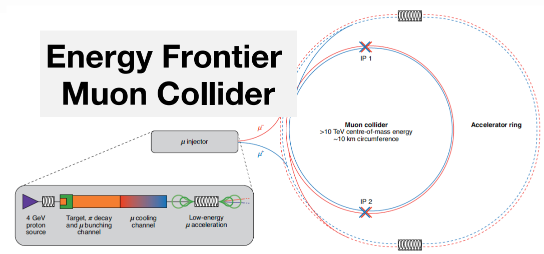
What is the nature of dark energy in the ΛCDM paradigm.

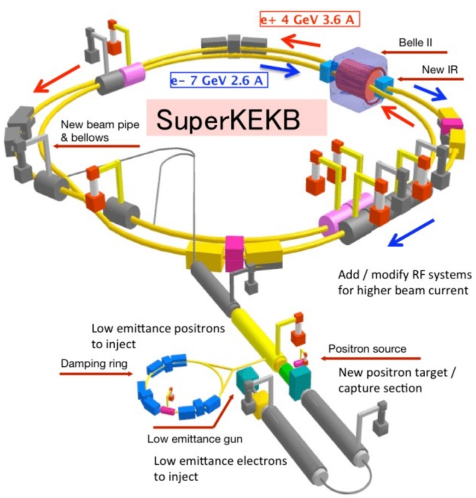


Search for Direct Evidence of New Particles



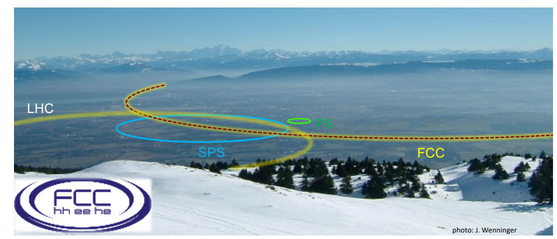


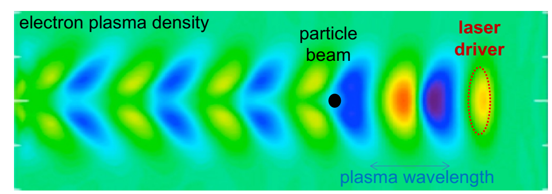




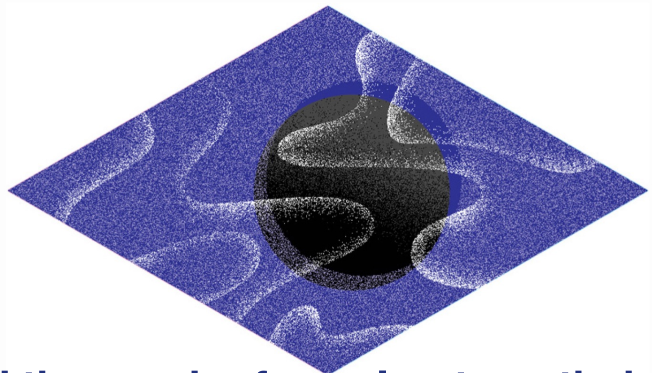
High-energy colliders enable exploration of the the unknown
Potential for discoveries beyond our current imagination
Access to high mass scales and new physics weakly coupled to the Standard Model

Searches are driven by:
Specific theories.
Previous observations.
Model independent exploration.





Pursue Quantum Imprints of New Phenomena

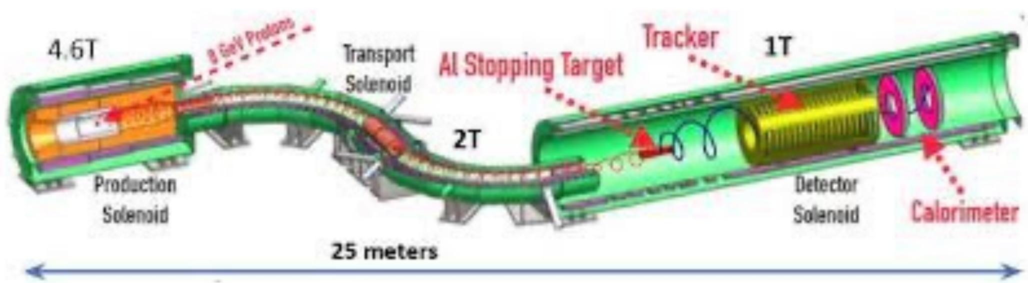


Even when particles are beyond the reach of accelerators, their quantum imprints might be seen.

Flavor physics is particularly sensitive to quantum imprints of particles that are not present in either the initial or final state of interactions.

Progress is built on clean theoretical predictions, precision techniques, and exquisite control of systematic effects.

Mu2e Experiment
Charged Lepton
Flavor Violation



2

The Recommended Particle Physics Program

Overview of the Recommended Particle Physics Program

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

- *Building upon the foundations laid by the previous P5*
- *…completes ongoing projects and capitalizes on their momentum*
- *A suite of new initiatives…that will shape the scientific landscape over the next two decades*

- *…carefully constructed to be compatible with the baseline budget scenario provided by DOE*
- *…continuing specific projects, strategically advancing some to the construction phase, and delaying others.*
- *…in some cases individual phases or elements of large-scale projects had to be prioritized separately*

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

Explorin
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Universe

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.

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ Higgs Factory
Neutrino Frontier	✓ LBNF/DUNE Phase I & PIP- II	✓ DUNE Phase II (incl. proton injector)
Cosmic Frontier	✓ Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	✓ Spectroscopic Survey - S5*	✓ Line Intensity Mapping*
	✓ Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		✓ Advanced Muon Facility

Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals of the next two decades. This table is not a timeline, rather large projects are listed by the decade in which the preponderance of their activity is projected to occur. Projects may start sooner than indicated or may take longer to complete, as described in the frontier reports. Projects were not prioritized, nor examined in the context of budgetary scenarios. In the observational Cosmic program, project funding may come from sources other than HEP, as denoted by an asterisk.*

✓ Recommended

✓ R&D

The particle physics case for studying gravitational waves at all frequencies should be explored by expanded theory support.

Recommendations Relevant to Future Muon Collider Development

Including comments relevant to achieving our goals

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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.

Recommendation 4 & MC Activities

4a) 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 [see sections 3.2, 5.1, 6.5, and also Recommendation 6]

4c) Expand the General Accelerator R&D (GARD) program within HEP, including stewardship [see section 6.4]

4d) 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… [see sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3]

4g) 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 [see section 6.6]

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Recommendation 5

Not Rank-Ordered

Professional Conduct, Engagement, Work Climate, Training and Dissemination of Results to the Public

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.

Recommendation 6

We can (and must) be ready for key decisions within the next decade!

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.

2.5 International and Inter-Agency Partnerships

Achieving any of our goals requires strong international partnerships!

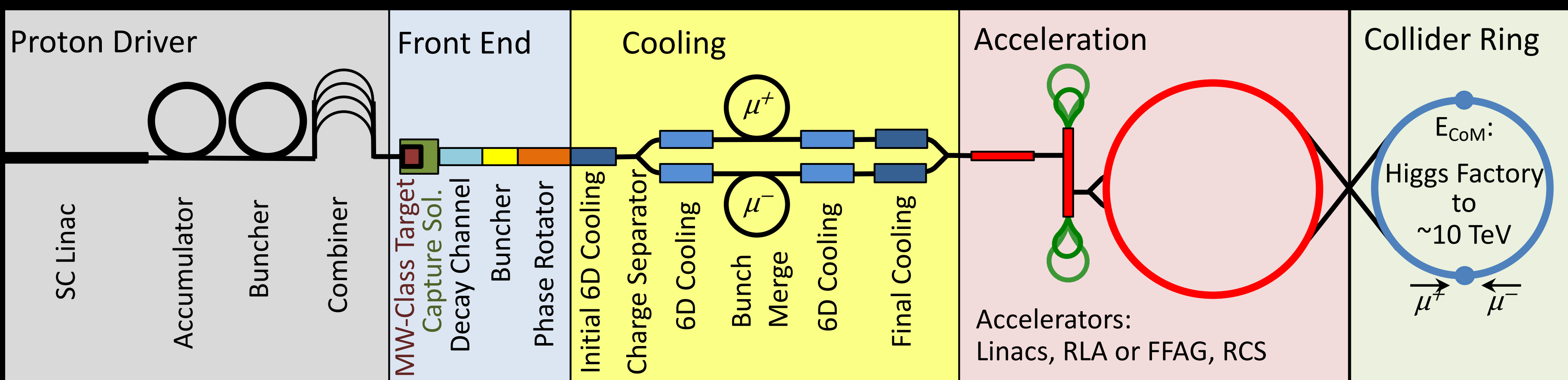
In the case of the Higgs factory, crucial decisions must be made in consultation with potential international partners. The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale. The ILC 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).

Next Steps for the US Program

Proton-Driven MC Concept

Muon Collider



Short & intense proton bunches to deliver hadronic showers

p→π→μ
→ bunched beams

Ionization cooling reduces the transverse & longitudinal emittance

Rapid acceleration to high energy to avoid μ losses. Multi-pass acceleration offers energy efficiency.

μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

Accelerator design is driven by the short muon lifetime

Brookhaven National Laboratory

P5 “Ask” from the US MC Community

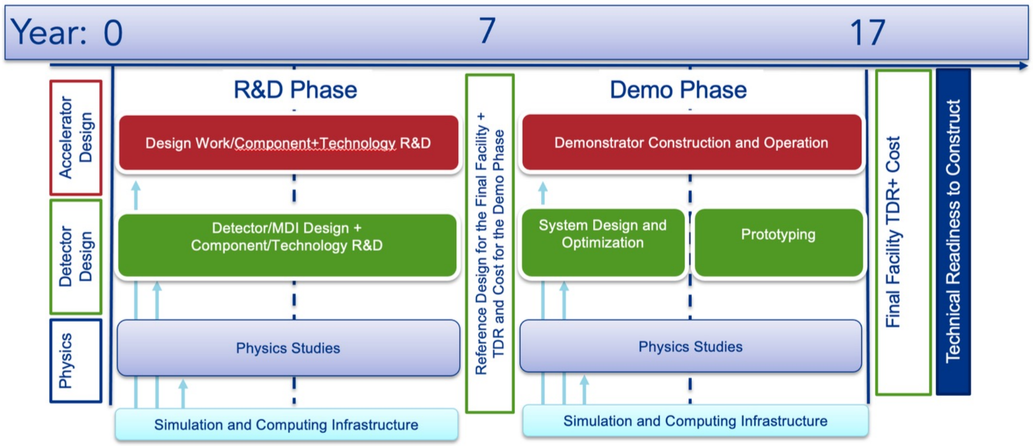


Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.

S. Jindariani, D. Stratakis, Sridhara Dasu et al.

- Aims for the US to be a co-equal partner with Europe in an International Effort
- Timeline trails the European “technically-limited” roadmap somewhat

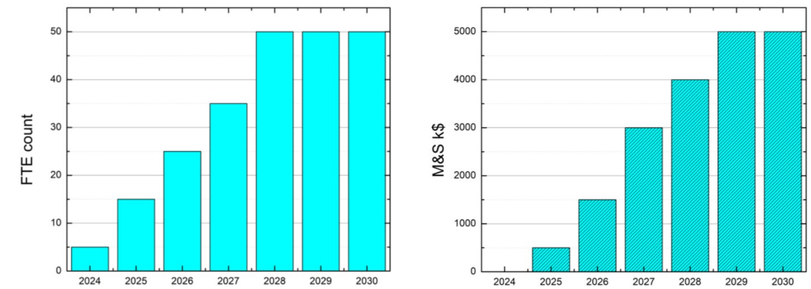


Figure 2: FTE and M&S profiles for accelerator R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

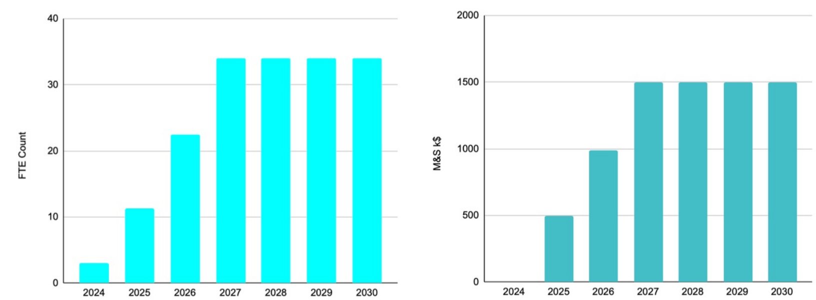


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

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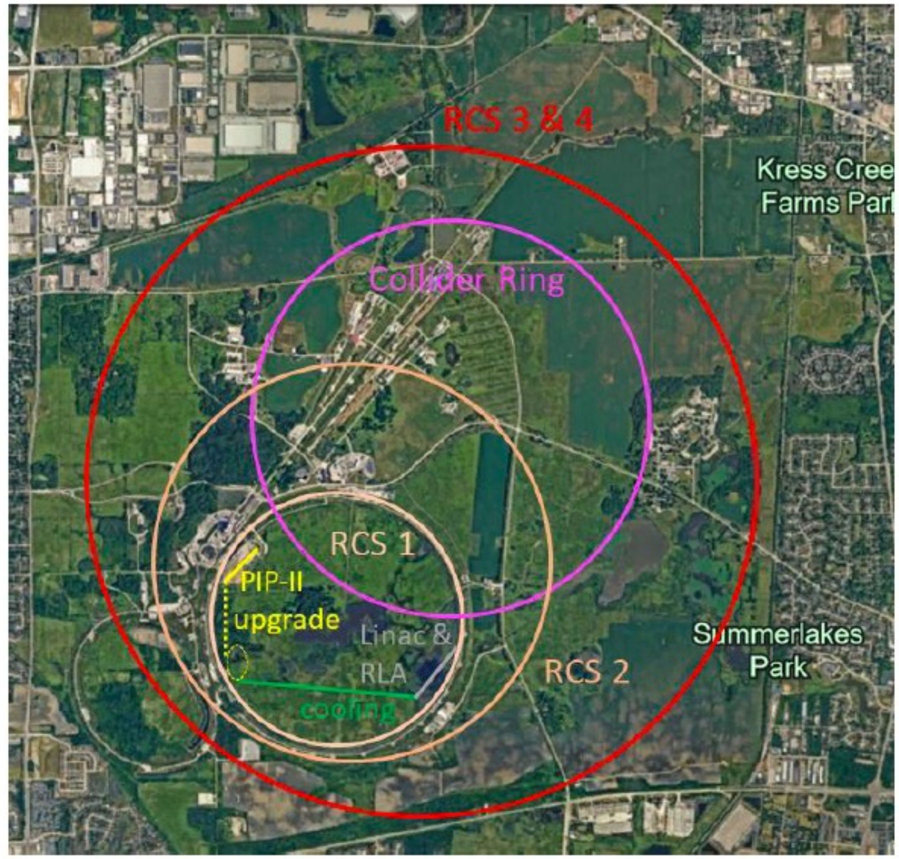
Muon Collider at Fermilab

- **10 TeV MuC** concept is in place
- Proton source
  - Post-ACE driver -> Target
- Ionization cooling channel
- Acceleration (4 stages)
  - Linac + RLA → **173 GeV**
  - RCS #1 → **450 GeV (Tevatron size)**
  - RCS #2 → **1.7 TeV (col. ring size)**
  - RCS #3, 4 → **5 TeV (site fillers)**
- Collider ring, 10.5 km long
  - Could be combined with RCS #2



- In the next years we like to have a baseline design including a neutrino flux mitigation system

Courtesy D. Stratakis

Key Steps Forward

- The US Particle Physics Community is ready to engage with Detector and Physics efforts to deliver the necessary concepts for a 10 TeV pCM capability
- Accelerator expertise exists for all parts of the envisioned machine
  - Must engage strongly with the international effort to achieve a technically limited timeline
    - *It cannot be overstated as to how critical it will be to achieve timely progress!!*
  - Options for early engagement are being explored
    - *US budgetary headwinds present a challenge*
    - *The GARD program can provide some basic technology development support*
    - *Individual laboratories have some flexibility*
    - *We hope for (and must advocate for) some rebalancing within existing US program*
  - Options for US siting are closely tied to the Fermilab ACE planning effort
- We anticipate that US MC activities will eventually be part of a DOE-HEP targeted US Collider R&D Program

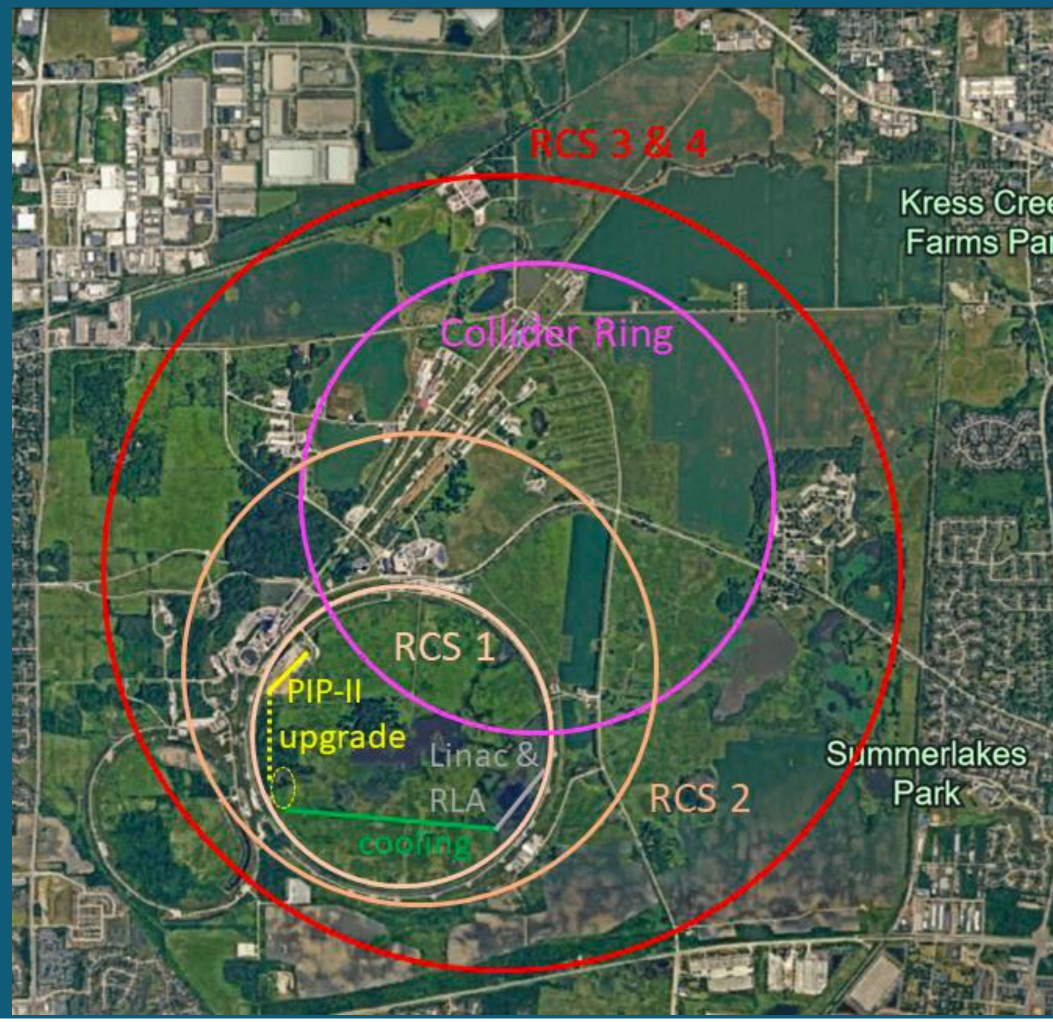
Conclusion

- A 10 TeV pCM Muon Collider R&D and design effort is currently underway!
- The 2023 P5 Report recommends establishment of a robust US Collider R&D Program
  - Both for a Higgs Factory and towards future 10 TeV pCM machines
  - With the aspiration for the US to host a future machine
  - Any of these machines will be a global endeavor
- For the US MC community, engagement with the international effort is the next critical step
  - Achieve a critical mass of world-wide expertise for the R&D and Design efforts
  - Ensure that R&D and design schedules can deliver results that support a machine decision within the 20-year time frame
- Challenges do exist…
  - DOE-HEP funding is not presently at the levels assumed in the P5 Scenarios
  - Time will be required to ramp up a well-managed effort
  - International agreements need to be put in place
  - The shape of the US Collider R&D Program needs to be defined

⇨ ***Looking forward to growing a US team to engage in the Muon Shot!***

Thank you for your attention!

The potential scale of the accelerator complex for a 10 TeV MC at Fermilab



Brookhaven National Laboratory

International MUON Collider Collaboration

Thank you for your attention!

Questions?

Brookhaven National Laboratory

P5 Area Recommendations

$$$ values are based on the funding guidance in Scenario B

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.**

Exploring the Quantum Universe

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.

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.

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.**