Panel recommends road map for US particle physics

The community welcomes the recommendations, recognizing them as fair and balanced within a constrained budget.

The High-Luminosity Large Hadron Collider. The Deep Underground Neutrino Experiment (DUNE). The Vera C. Rubin Observatory. Completing and supporting such ongoing projects is the highest priority in the recommendations for particle physics for the next decade and beyond, as laid out in *Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics*. The report was released on 7 December by the US Particle Physics Project Prioritization Panel (P5).

Among new large projects, the panel taps the Cosmic Microwave Background Stage 4 experiment at the South Pole and Chile as the top priority. It sets paths for supporting a Higgs factory, a next-generation particle collider, dark-matter searches, and an upgrade to DUNE. It emphasizes maintaining balance in terms of the science addressed, the size and time scales of projects, and the locations of experiments in and outside the US. It also stresses the importance of experimental and theoretical research and workforce training. (See the chart on page 21.)

The Department of Energy and NSF charged the panel with formulating strategies given two budget scenarios. Both start from the 2023 annual funding for particle physics from DOE of nearly $1.2 billion. The better scenario involves a boost over five years from the CHIPS (Creating Helpful Incentives to Produce Semiconductors) and Science Act and an annual increase by a projected inflation rate of 3%. By 2033, funding would be $1.85 billion. The less favorable one supposes funding increases at just 2% a year, reaching $1.45 billion by the end of the period. Funding from NSF for particle physics is much smaller and comes from multiple offices; it is omitted from the scenarios.

A broad portfolio

Hitoshi Murayama, a theoretical physicist at the University of California, Berkeley, chaired the 32-member P5. The biggest challenge, he says, was winnowing the huge number of ideas generated by the community (see Physics Today, October 2022, page 22). Despite many ideas having been left on the back burner to fit into constrained budgets, the community has widely embraced the panel's recommendations. As of mid January, more than 3100 particles physicists, mostly from the US and across all career stages and subfields, had signed a letter in support of the P5 road map.

In the past, the sought-after physics was known, says Julia Gonski, a collider physicist who last fall started a tenure-track-equivalent position at SLAC. "There had to be a Higgs particle. Now it's the Wild West. Instead of looking in depth, we need a broad search. We have to look for anything that could be a deviation from the standard model. Hints will become a compass to follow." That uncertainty represents a cultural shift in particle

A COSMIC MICROWAVE BACKGROUND EXPERIMENT got top marks from the latest Particle Physics Project Prioritization Panel. The Stage-4 CMB would consist of one 5-meter and nine 0.56-meter telescopes at the South Pole, near the existing CMB experiments (shown here) and two 6-meter telescopes in Chile's Atacama Desert.

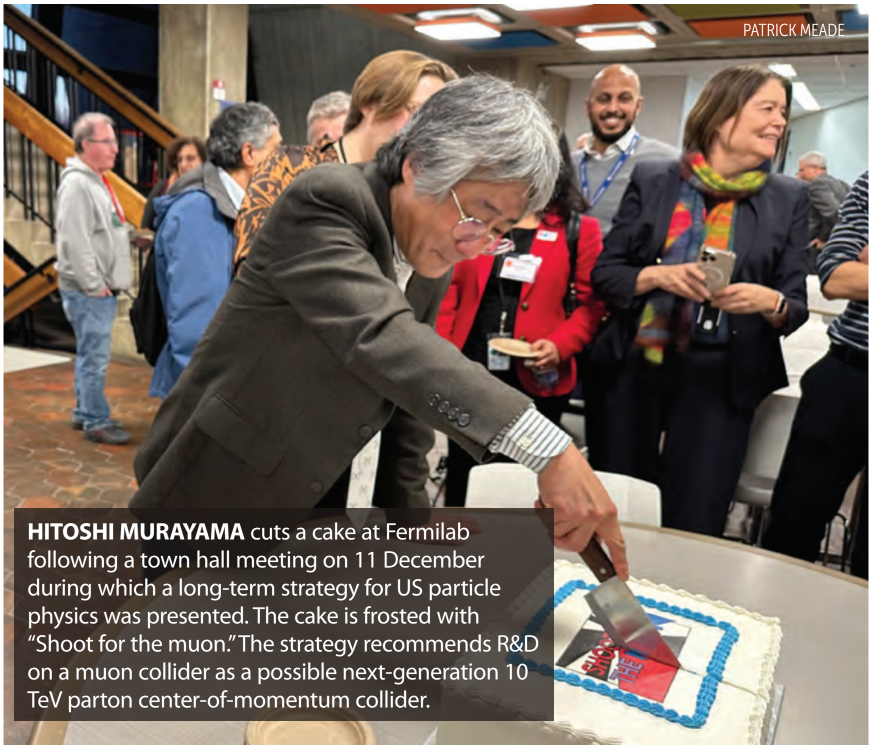
physics, she says. "P5 delivered a nice strategy that should be very exciting to the early-career community."

The major projects, defined as having a price tag that exceeds $250 million, are the only five that the panel recommended in ranked order (see table on page 20). Among the medium-scale ($50 million–$250 million) projects P5 recommends are contributions to upgrades to US and international experiments that study cosmic evolution, search for dark matter, and detect particles and phenomena from hints remaining from quantum fluctuations in the early universe.

The panel also recommends that DOE create a program to fund small projects, called Advancing Science and Technology Through Agile Experiments. The program should be funded at $35 million a year and put out regular calls for small projects that can see results in a few years, the report says. The aim is to allow for creativity, exploration, and training.

Funding for theoretical research at universities should be increased by about $15 million a year—over the current $55 million to $60 million—to bring such support back to 2010 levels, the report says. That and increases in other areas of research are intended to pave the way for future innovation and ensure international competitiveness.

"Research is where creativity shines, where you take a gamble and allow people to be creative and find things that might be big in the future," says P5 member Abigail Vieregg, a cosmologist at the University of Chicago. "In-



HITOSHI MURAYAMA cuts a cake at Fermilab following a town hall meeting on 11 December during which a long-term strategy for US particle physics was presented. The cake is frosted with "Shoot for the muon." The strategy recommends R&D on a muon collider as a possible next-generation 10 TeV parton center-of-momentum collider.

vesting in research is critically important. It's not just about building big flagship projects."

Overall, the total projected particle-physics budget scenario is broken down into roughly a third each for research, projects, and operations.

The loudest pushback that P5 members have received regards five experiments that would piggyback on the Large Hadron Collider to explore neutrinos and dark matter. "I am very disappointed," says Shih-Chieh Hsu, an experimental particle physicist at the University of Washington. "Although I support the report, I had hoped that P5 would be more friendly to cultivating such a facility." The report suggests that if CERN does proceed with the required civil engineering, the experiments could apply individually for funding under the small-projects portfolio it recommends.

Shooting for the muon

The report recommends "vigorous R&D toward a cost effective" 10 TeV parton center-of-momentum (pCM) collider. Such a collider would explore energies roughly an order of magnitude higher than are accessible with the Large Hadron Collider. It could be based on protons or muons, or on wakefield or other new accelerator technologies that would make linear colliders shorter and cheaper.

US particle physicists are especially excited about the possibility of a muon collider. As fundamental particles, muons would need to be accelerated to 10 TeV to achieve 10 TeV pCM, rather than the 100 TeV that a proton collider would require. That means that the facility could be smaller and could fit on the Fermilab campus. "Hosting the next major collider on US soil would be fantastic," says Patrick Meade, a theoretical physicist at Stony Brook University.

The idea for a muon collider came up short in the previous P5 report, from 2014, because of the challenges. Muons have a lifetime of just 2.2 microseconds and would have to be cooled, bundled, and collided within that window.

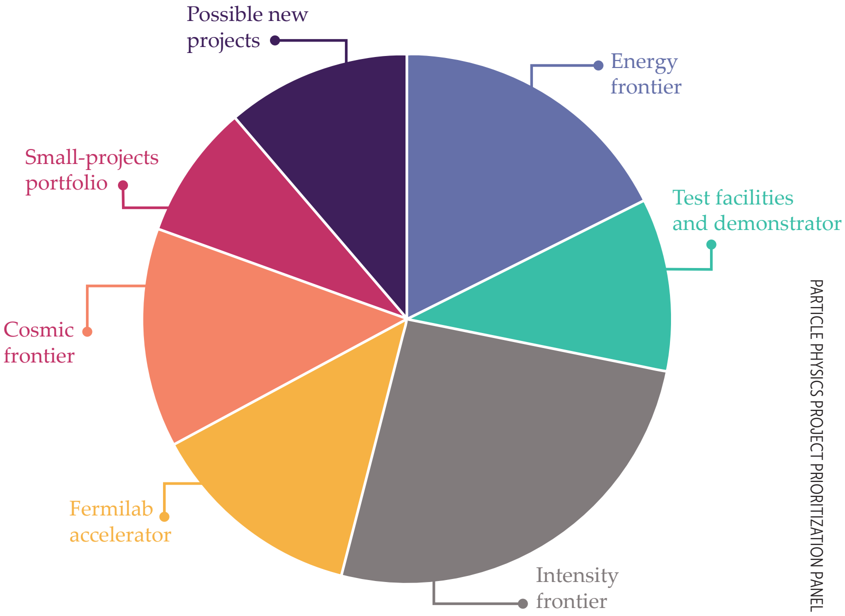
But progress in technology has revived interest in a muon collider. For example, the strong superconducting magnets developed for the ITER fusion experiment didn't exist a decade ago, and a similar technology could be used to collect muons, says Meade. "All the pieces of technology exist as independent components," he says. "We need to bring them together to make a demonstrator and show that a muon collider is possible."

Because muons are heavier than electrons, they have the advantage of producing less synchrotron radiation, and as they are accelerated to higher energies, they live longer because of time dilation. "Muons give you the best of

Major new projects, from highest to lowest priority

Project	More favorable budget scenario	Less favorable budget scenario
Cosmic Microwave Background Stage 4	The CMB-S4 would study light from the beginning of the universe to search for signatures of primordial gravitational waves, probe dark matter and dark energy, and more. It would consist of one 5-meter and nine 0.56-meter telescopes at the South Pole and two 6-meter telescopes in Chile's Atacama Desert.	No reduction in scope.
Deep Underground Neutrino Experiment, phase 2	The upgrade would comprise an early enhancement of the facility's accelerator at Fermilab, a third underground detector module 1300 kilometers away at the Sanford Underground Research Facility (SURF), and an upgrade to the facility's near-detector complex. The main goal for phase 2 is to seek neutrino–antineutrino asymmetry.	Proceed with the third far detector; defer upgrades to the accelerator and near detector.
US investment in an off-shore, international Higgs factory	The candidates are a 97-kilometer circumference electron–positron collider at CERN and the International Linear Collider, a mature design that Japan has been considering hosting for years.	Reduce and delay contributions.
Generation 3 dark-matter experiment	The experiment would search for dark matter—specifically weakly interacting massive particles.	No SURF expansion or US-based G3 dark-matter experiment; reduce participation in experiment outside the US.
IceCube-Gen2	The expansion would improve the sensitivity of NSF's Antarctic neutrino observatory 10-fold by increasing its volume and number of sensors. Among other aims, IceCube-Gen2 would identify high-energy astrophysical neutrino sources and determine their flavor ratios. It would look for neutrino signatures beyond the standard model.	No reduction in scope.

Based on information in *Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics*.



PARTICLE PHYSICS PROJECT PRIORITIZATION PANEL

SCIENTIFIC BALANCE AND DIVERSITY are among the goals of the latest long-term strategy for US particle physics. The chart shows a snapshot of investment areas for 2033 if the strategy's recommendations are implemented.

both worlds: high energies and precision simultaneously," says Meade. Many unknowns remain, but a muon collider would likely cost in the neighborhood of $10 billion, he says.

CERN and China are considering 100 TeV colliders. They would first build an electron–positron collider some 100 kilometers in circumference, and then upgrade it to collide protons. (See "China plans a Higgs factory," Physics Today online, 17 December 2018, and "CERN considers a 100 TeV circular hadron collider," Physics Today online, 5 February 2019.) "It's too early to get behind any single machine," says SLAC's Gonski. If the Future Circular Collider at CERN goes forward, it would be ready for data taking in 2045 in its initial electron–positron incarnation, and in 2070 as a proton collider. It would be the last iteration of going bigger to get to higher energies, says Gonski. "We won't build a 1000-kilometer ring next time. For long-term success, we need to get to smaller footprints."

The P5 report sets a goal of being ready to build test and demonstrator facilities for 10 TeV pCMs within 10 years. It also recommends convening task forces to evaluate the options and specify next steps once more information is available.

Leadership loss

If funding turns out to be closer to the less favorable scenario, some aspects of the DUNE upgrade and many other projects would be curtailed or delayed. The recommendation to dig a new cavern for a third-generation dark-matter experiment at the Sanford Underground Research Facility in South Dakota would be replaced with contributing to an experiment outside the US (see table). Theory funding would be increased less, and support for small projects through the Advanced Science and Technology Through Agile Experiments program, as well as computing, instrumentation, and collider R&D, would be slashed.

The lower budget scenario "represents erosion," says Murayama. "It would result in the US losing leadership in many areas." It would also cast doubt on the US as a reliable partner in international projects, he says. Now he and colleagues are busy briefing policymakers and government agencies to muster support for funding their field.

Toni Feder