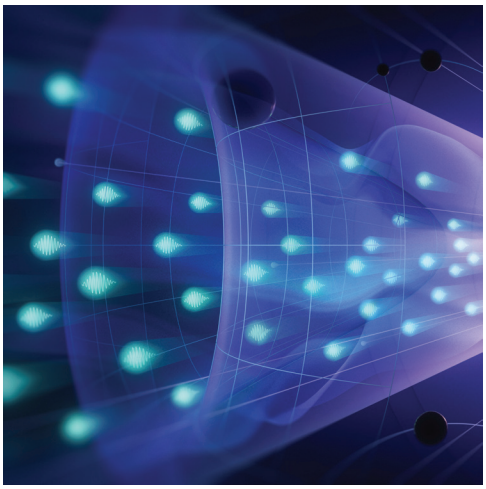
Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Draft for Approval

Particle physics studies the smallest constituents of our vast and complex universe. At such small scales, the fundamental principles of quantum physics prevail. Remarkably, the entire observable universe, now billions of light years across, was once so small as to be quantum in nature. This quantum history of the universe is imprinted on its large-scale structure.

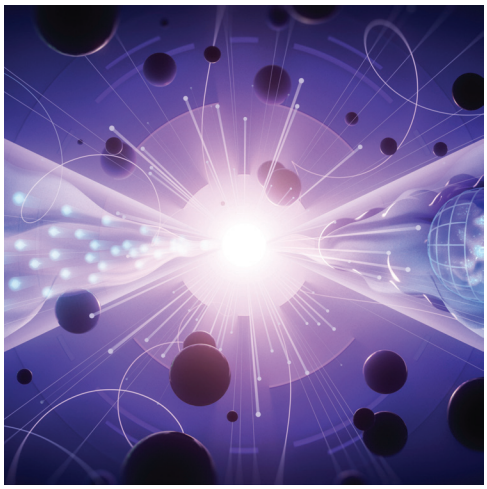
The recommended program describes particle physics in three science themes. Within each of these themes we identify two focus areas, or science drivers, that represent the most promising avenues of investigation for the next 10 to 20 years.



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

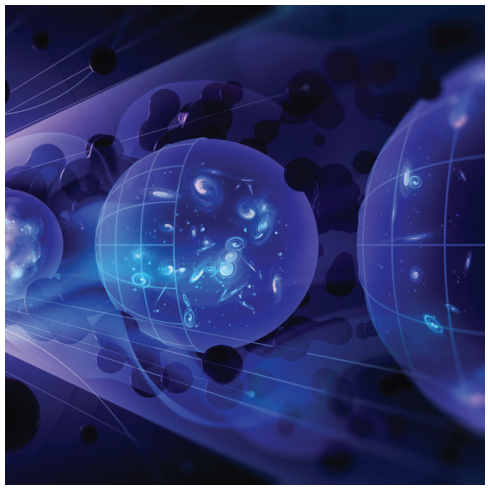
Reveal the Secrets of the Higgs Boson



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

Past successes in particle physics have revolutionized our understanding of the universe and prompted new sets of questions. Collectively, these questions have spurred the construction of state-of-the-art facilities, from particle accelerators to telescopes, that will illuminate the profound connections between the very small and the very large. Recent investments in the High-Luminosity Large Hadron Collider (HL-LHC) at CERN, the Deep Underground Neutrino Experiment (DUNE), and the Vera C. Rubin Observatory (Rubin) have positioned the US to continue its leadership in particle physics. Working with our international partners, we stand on the threshold of harnessing the full potential of these facilities.

Vision of the 2023 Particle Physics Project Prioritization Panel (P5)

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. Particle physics has a long-proven record of creating new technologies and provides a training ground for a skilled workforce that drives not only fundamental science, but quantum information science, AI/ML, computational modeling, finance, national security, and microelectronics.

We recommend the following:

As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. This includes HL-LHC, the first phase of DUNE and PIP-II, the Rubin Observatory to carry out the Legacy Survey of Space and Time (LSST), and the LSST Dark Energy Science Collaboration.

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.

1. **CMB-S4**, which looks back at the earliest moments of the universe,
2. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam as the definitive long-baseline neutrino oscillation experiment,
3. **Offshore Higgs factory, realized in collaboration with international partners**, in order to reveal the secrets of the Higgs boson,
4. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,
5. **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter.

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. The proposed portfolio includes implementing the recommended program, Advancing Science and Technology using Agile Experiments (ASTAE).

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 parton center-of-momentum (pCM) collider. In particular, the muon collider option builds on Fermilab strengths and capabilities and supports our aspiration to host a major collider facility in the US.

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.