



Three frontiers of research in particle physics form an interlocking framework that addresses fundamental questions about the laws of nature and the cosmos.

The Three Frontiers of Particle Physics

What are the most basic building blocks of the universe? What are the forces that enable these elementary constituents to form all that we see around us? What unknown properties of these particles and forces drive the evolution of the universe from the Big Bang to its present state, with its complex structures that support life—including us? These are the questions that particle physics seeks to answer.

Particle physics has been very successful in creating a major synthesis, the Standard Model. At successive generations of particle accelerators in the US, Europe and Asia, physicists have used high-energy collisions to discover many new particles. By studying these particles they have uncovered both new principles of nature and many unsuspected features of the universe, resulting in a detailed and comprehensive picture of the workings of the universe.

Recently, however, revolutionary discoveries have shown that this Standard Model, while it represents a good approximation at the energies of existing accelerators, is incomplete. They strongly suggest that new physics discoveries beyond the Standard Model await us at the ultrahigh energies of the Terascale. The Large Hadron Collider will soon provide a first look at this uncharted territory of ultrahigh energy; a future lepton collider will elucidate the new phenomena with great precision.

A striking development in neutrino physics is the discovery that the three kinds of neutrinos, which in the Standard Model are massless and cannot change from one type to another, do in fact have tiny masses and can morph from one kind to another. This discovery has profound implications not only for the Standard Model but also for understanding the development of the early universe.

The accelerating expansion of the universe, yet another remarkable discovery, implies the existence of a mysterious entity, a dark energy that makes up almost three quarters of the energy-matter content of the universe, driving it apart at an ever-increasing rate. Dark Energy has interesting properties that could change our understanding of gravity.

Astrophysical observations have also revealed that about a quarter of the universe consists of an unknown form of matter called dark matter. No Standard Model particle can account for this strange ingredient of our universe. In the next decade, the combination of LHC results and dedicated dark-matter-search experiments promise to shed light on dark matter's true character.

All these discoveries make the field of particle physics richer and more exciting than at any time in history. New accelerator and detector technologies bring within reach discoveries that may transform our understanding of the physical nature of the universe.

A set of interrelated questions, articulated in several previous reports, defines the path ahead:

1. How do particles acquire mass? Does the Higgs boson exist, or are new laws of physics required? Are there extra dimensions of space?
2. What is the nature of new particles and new principles beyond the Standard Model?
3. What is the dark matter that makes up about one quarter of the contents of the universe?
4. What is the nature of the dark energy that makes up almost three quarters of the universe?

5. Do all the forces of nature become one at high energies? How does gravity fit in? Is there a quantum theory of gravity?
6. Why is the universe as we know it made of matter, with no antimatter present? What is the origin of this matter-antimatter asymmetry?
7. What are the masses and properties of neutrinos and what role did they play in the evolution of the universe? How are they connected to matter-antimatter asymmetry?
8. Is the building block of the stuff we are made of, the proton, unstable?
9. How did the universe form?

Physicists address these questions using a range of tools and techniques at three frontiers that together form an interlocking framework of scientific opportunity.

The Energy Frontier

Experiments at energy-frontier accelerators will make major discoveries leading to an ultimate understanding of particles and their interactions. Outstanding questions that present and future colliders will address include the origin of elementary particle masses, the possible existence of new symmetries of nature, the existence of extra dimensions of space, and the nature of dark matter. Experiments at the energy frontier, at the LHC and at a future lepton collider, will allow physicists to directly produce and study the particles that are the messengers of these new phenomena in the laboratory for the first time.



The Intensity Frontier

Measurements of the mass and other properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for the understanding of the evolution of the universe. The US program can build on the unique capabilities and infrastructure at Fermilab, together with the proposed deep underground laboratory at Homestake, to develop a world-leading program of neutrino science. Such a program, not possible at the large collider facilities, will require a multi-megawatt-powered proton source at Fermilab. Incisive experiments using muons, kaons or B mesons to measure rare processes can probe the Terascale and beyond.



The Cosmic Frontier

Ninety-five percent of the contents of the universe appears to consist of dark matter and dark energy, yet we know very little about them. To discover the nature of dark matter and dark energy will require a combination of experiments at particle accelerators with both ground- and space-based observations of astrophysical objects in the distant cosmos.



The three frontiers of research in particle physics form an interlocking framework that addresses fundamental questions about the laws of nature and the cosmos.

These three approaches ask different questions and use different techniques, but they are ultimately aimed at the same transformational science. Discoveries on one frontier will have much greater impact taken together with discoveries on the other frontiers. For example, the discovery of new particles at the energy frontier, combined with discoveries from the intensity frontier about neutrinos and rare processes, may explain the dominance of matter over antimatter. Synthesizing discoveries from all three frontiers creates the opportunity to understand the most intimate workings and origins of the physical universe.