## Chapter 2. Fermilab and the Quantum Universe

Particle physicists are on a 21st-century quest to answer profound questions about the universe. Powerful new scientific tools for particle physics and astrophysics now bring the answers to these compelling questions within reach. Along with astrophysical observations, particle accelerators offer different paths to the exploration of the physics of the Quantum Universe. At the energy frontier, the Large Hadron Collider at CERN and the proposed International Linear Collider will take physicists into a new "Terascale" energy region and the discoveries it holds. High-intensity accelerators offer another pathway to discovery by opening the door into the world of neutrinos and precision physics, where physicists expect they will also find answers to Quantum Universe questions.

* **0. What is the origin of mass for fundamental particles?**
* **1. Are there undiscovered principles of nature: new symmetries, new physical laws?**
* **2. How can we solve the mystery of dark energy?**
* **3. Are there extra dimensions of space?**
* **4. Do all the forces become one?**
* **5. Why are there so many kinds of particles?**
* **6. What is dark matter? How can we make it in the laboratory?**
* **7. What are neutrinos telling us?**
* **8. How did the universe come to be?**
* **9. What happened to the antimatter?**
* *Based on* "The Quantum Universe," *HEPAP 2004*

The energy-frontier machines, the LHC and the proposed ILC, give physicists the means of discovering new symmetries and new physical laws, of finding extra dimensions of space and of finally penetrating the mystery of the origin of mass. Understanding the nature of dark matter will require energy-frontier accelerator programs to produce dark matter and analyze its properties. With the Tevatron running and the LHC nearing completion, the adventure of Terascale science has begun. Experiments at the LHC, built in Europe with U.S. participation, will provide a clear look at the Terascale. Hundreds of U.S. particle physicists will join collaborators from around the world in the largest scientific experiments ever conducted.

Physicists plan to build on the discoveries at the LHC with experiments at the proposed International Linear Collider. The ILC would allow experimenters to explore the new scientific landscape of the Terascale, revealing the properties of new phenomena and building the foundation for a clear and consistent understanding of this new energy terrain. Beyond this, precision measurements from the ILC could act as a telescope to reveal secrets from the much higher energies of the ultimate unification of forces and of matter.



**Neutrino mass hierarchy**
How do neutrino masses stack up? The answer depends on how forces and matter become one—if they do.

Neutrino experiments, which have recently succeeded in detecting new physics, open their own window on unification, the question whether all the forces and particles of matter become one. Neutrinos have the unique potential to explain our cosmic beginnings from a process called leptogenesis. As part of Fermilab's world-class program in neutrino science, the laboratory has embarked on the NOνA experiment. NOνA will provide the first chance at determining the ordering of neutrino masses, a key piece of information for understanding the role of neutrinos in unification. The joint power of the Japanese T2K (Tokai to Kamioka) experiment and NOνA will be the first step toward experiments using high-intensity neutrino beams to detect the matter-antimatter properties of neutrinos that leptogenesis requires. Neutrino discoveries could link up with LHC or ILC discoveries of phenomena such as supersymmetry or with a charged-lepton-flavor-violation experiment, the morphing of one kind of charged lepton to another.

As the U.S. particle-physics community embarks on this global journey of discovery, the Particle Physics Project Prioritization Panel subpanel of the High Energy Physics Advisory Panel in 2006 laid out a roadmap for particle-physics research over the next decade in the United States. The P5 roadmap set priorities for U.S. particle physics aimed at maximizing the potential for discovery. Fermilab is strategically aligned with the P5 roadmap with a research program of

* energy-frontier physics starting with the Tevatron, continuing with the Large Hadron Collider, and following with the proposed International Linear Collider,
* accelerator-based neutrino physics,
* particle astrophysics including dark matter and dark energy.

The P5 roadmap charts a course for U.S. particle physics at a key moment in the life of the field. While accelerator-based particle physics is exciting and strong internationally, particle physics in the United States is confronting a very challenging period. By the end of the decade, the world-class programs at the Tevatron, the SLAC *B* Factory and Cornell's CESR will be complete. The contributions of U.S. facilities to global particle physics will then come solely from the Main Injector at Fermilab for a neutrino physics program, and from a test-beam program for evaluating new and innovative detector concepts. In the U.S., an era of world-leading accelerator-based science at the energy frontier will come to an end. On the other hand, the conclusion of research at these U.S. accelerator facilities provides an opportunity to redirect resources toward hosting the ILC in the U.S. in order to continue the nation's historical role as a world leader in the science of particle physics.

**Did we all come from neutrinos?**

Leptogenesis, from the Greek for "delicate origins," is the theory that all visible matter (stars, planets, people) comes from neutrinos. The cooling fireball of the big bang produced matter and antimatter directly, but in nearly equal amounts. Precise measurements of elementary particles show that the cosmic annihilation of matter and antimatter was almost complete, leaving not nearly enough leftover matter to form the billions of stars that we see today. Where did all this matter come from? Leptogenesis could be the answer.

The theory of leptogenesis starts with the observation that neutrinos are very different from other kinds of matter. Theorists postulate that neutrinos may be the only matter particles that are their own antiparticles. If so, it means that they obey a different set of rules with respect to the symmetry between matter and antimatter, or CP symmetry. Neutrinos also have superlight masses, which to physicists suggests a "see-saw" with superheavy partner neutrinos, not yet detected.

When theorists rerun the tape of the big bang introducing superheavy partner neutrinos that have nonstandard CP symmetry, the result is leptogenesis. The heavy neutrinos fall apart into light neutrinos, producing an excess of matter over antimatter. In the hot environment of the early universe, this excess is quickly passed along to all the particles that we are made of. If the theory of leptogenesis is correct, we owe our existence to neutrinos from the big bang.

Throughout Fermilab's history, the heart of the laboratory's scientific research has been the quest to solve the mysteries of the universe using energy-frontier particle accelerators. Because of its unique discovery potential and its significance for the national program, the ILC is Fermilab's highest priority for the future. Fermilab is committed to leadership in the international effort to build the ILC as early as possible, and the laboratory is a strong contributor to the ILC's Global Design effort.

Following the technology choice for the ILC in 2004, the Global Design effort and the international ILC community produced a *Reference Design Report* in February 2007 and are currently preparing an engineering design, required for a decision to build the ILC, that will be complete in 2010.

The "technically driven" timeline for the ILC, based on technical readiness to proceed with the project, calls for a decision to go forward with the new collider in 2010 and for an ILC construction start early in the next decade. The P5 Panel assumed such a timeline in developing the roadmap for U.S. particle physics. However, because factors other than technical feasibility may postpone the start of the ILC, it becomes necessary to carefully plan the U.S. particle-physics program both to secure the ILC and to continue to contribute to particle physics discovery during a possibly extended period before the ILC can open up new scientific horizons.

The goal of the Steering Group is to provide a Fermilab plan for scientific discovery in accelerator-based particle physics. In line with the P5 priorities, the plan represents a strategy to ensure the continuing U.S. capability to address the compelling questions of particle physics using the unique scientific potential of particle accelerators. The plan is flexible, offering options to address the scientific opportunities and challenges facing particle physics in the U.S. today. It keeps the ILC as the central feature of the Fermilab accelerator-based particle-physics plan and advances progress on technologies that will be needed for future frontier accelerators, such as a muon collider. The plan provides discovery opportunities should the timeline for ILC construction stretch out for any number of reasons: physics results, federal funding decisions, international agreements, site decisions for the ILC or other factors. The Steering Group's proposed plan sustains the potential for accelerator-based discovery in the U.S. both at the energy frontier with the ILC and with intense proton beams in the event of a delayed ILC. Crucially, the plan strengthens ties with university scientists and other laboratories and provides scientific training and education for hundreds of graduate students, the next generation of particle physicists.



**The charged leptons**
Can one lepton change to another? If so, neutrino properties are pointing toward the unifi cation of matter, the origin of all the elementary particles we know today from one single kind of particle at the big bang.

**Unification and LFV**

In the Standard Model, the weak interactions connect the three kinds of neutrinos to the three particles known as charged leptons: electron, muon and tau. Since experiments have discovered that neutrinos change from one kind to another, physicists wonder if the charged leptons do too. By producing huge numbers of muons in a controlled environment, experimenters hope to observe the direct conversion of a muon into an electron. This would be the first observation of lepton flavor violation outside the world of neutrinos.

These and other hints from data point toward matter unification, the idea that all of the charged leptons, neutrinos and quarks arose from a single kind of superparticle in the first instant of the big bang. Theorists find that when they put the ideas of unification and supersymmetry together, their models predict LFV for charged leptons at a rate that next-generation experiments could detect.

In models of unification, LFV is related to the process of leptogenesis. LFV with charged leptons is sensitive to different parts of the mechanism of leptogenesis from those accessible by neutrino experiments. An experimental program combining neutrino science with muon-to-electron conversion experiments and energy-frontier searches for supersymmetry would be a powerful probe of our unified origins.

Particle physics has become an interconnected global enterprise, with overarching scientific priorities defining regional and national plans. A plan for any specific laboratory must be formulated as part of a national program that is in turn coordinated with plans from other regions. Any new facility is likely to have competition elsewhere, and the scientific challenges dictate the need for strong research capabilities in all regions. The Fermilab Steering Group is a step in an integrated planning process—in the U.S. through P5 and HEPAP and then in a fully global context.

For U.S. particle physics, the decade ahead will bring great scientific opportunity and difficult challenges. Our questions for the universe could not be more profound or more compelling, especially because the means to address them are at last within reach. How the university and laboratory community comes together with government to meet the challenges and rise to the scientific opportunities is likely to shape the course of particle-physics research in the United States for a long time to come. In this context, Fermilab has a unique responsibility as the nation's primary particle physics user facility. The Fermilab Steering Group proposes a plan for the laboratory that is pragmatic, scientifically exciting and flexible enough to meet the challenges of a still-unfolding future and to provide for Fermilab's users the greatest possible opportunity for scientific discovery.