## 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.

* **What are the origins of mass?**
* **What are the origins of matter?**
* **How did the universe come to be?**

At the energy frontier, experiments at the Large Hadron Collider are probing a new energy region for whatever discoveries it holds. These discoveries could include contact with new phenomena that generate mass for elementary particles: perhaps the Higgs with its related particles and forces, or perhaps a new strong force that mimics how nucleons obtain mass from quantum chromodynamics. Precision measurements, at the Tevatron and elsewhere, of the quantum consistency of the Standard Model hint at a relatively light Higgs boson, but the LHC may reveal a more complex picture with unexpected twists and turns. Over the next two decades or more, the story of the origin of mass is likely to involve new forces of nature, new energy regimes, and fundamental symmetries beyond the Standard Model.

At the intensity frontier, experiments at Fermilab and other laboratories have recently discovered many surprising properties of neutrinos, the most mysterious elementary particles yet observed. Neutrinos have tiny masses at least a million times smaller than the next lightest particle. Neutrinos are the only known elementary particles that morph from one flavor to another as they travel over long distances; this quantum process may also connect them to even more exotic “sterile” particles that are immune to Standard Model forces. The novel properties of neutrinos dramatize the larger question of the origins of matter: there are 45 known “elementary” matter particles, whose quantum properties show a bewildering variety but also suggest unified origins. Ideas about the unified origins of matter can be tested in new experiments at the intensity frontier. The Mu2e experiment at Fermilab may show that charged leptons morph in flavor, like their neutral cousins the neutrinos.

This new phenomenon, in turn, has a natural quantum connection to effects that could be detected in a Fermilab g-2 experiment, or in experiments detecting tiny electric dipole moments. Observing rare decays of kaons at Fermilab would give a unique window on the properties of quarks, and anomalies seen there could be tied to new physics at the energy scale of the LHC or beyond. Just as key observations in chemistry and spectroscopy led from the periodic table to the quantum basis of atomic structure, the next decades may yield the clues to the unified origins of matter at a more fundamental level.

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 already embarked on the NOνA experiment. providing 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 detecting the matter-antimatter properties of neutrinos that leptogenesis requires. Neutrino discoveries could link up with LHC discoveries of phenomena such as supersymmetry and with charged-lepton-flavor-violation if discovered in the Mu2e experiment.

**Do 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 Big Bang produced matter and antimatter directly, but in nearly equal amounts. The cosmic annihilation of matter and antimatter should have been 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, and 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; to physicists this suggests that the origin of neutrino mass involves both the Higgs and an additional shorter-range interaction with hypothesized superheavy neutrinos. This "see-saw" with superheavy partner neutrinos could provide an experimental window to leptogenesis.

When theorists rerun the tape of the Big Bang introducing superheavy partner neutrinos with 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.

At the cosmic frontier, Fermilab is already leading searches with CDMS and COUPP aimed at finding the identity of dark matter. Once direct detection of dark matter particles is confirmed, it will be an even greater challenge to link this discovery to the formation of structure in the cosmos, to the possibility of producing dark matter in LHC collisions, or to possible signals of dark matter annihilation in our galaxy. The effects of dark matter on the evolution of the expanding universe is entwined with the even more mysterious role of dark energy, but here again Fermilab is already at the forefront with the Dark Energy Survey.

Throughout Fermilab's history, the heart of the laboratory's scientific research has been the quest to solve the mysteries of the universe using particle accelerators. 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. In this context, Fermilab has a unique responsibility as the nation's primary particle physics user facility. The Fermilab strategic plan is pragmatic and flexible enough to meet the challenges of a still-unfolding future, but most importantly it will provide Fermilab's users with the greatest possible opportunities for scientific discovery.



**The charged leptons**

**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.

Aleardy 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.