Discovery at Fermilab: The Next Twenty Years

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Introduction

The Fermilab Long Range Planning Committee wrote their excellent report, *The Coming Revolution in Particle Physics,* in response to a charge to describe alternative scenarios for Fermilab in the next decade. Drawing on their report, I have written this brief document to give a vision of the next twenty years of discovery at Fermilab. I will also describe what we are doing now to optimize the future opportunities for discovery.

While the Fermilab committee was working on their report, another committee was at work on *The Quantum Universe*, in response to a charge to the High Energy Physics Advisory Panel by Dr. Raymond L. Orbach, Director of the Office of Science of U.S. Department of Energy and Dr. Michael Turner, Assistant Director for Mathematics and Physical Science of the National Science Foundation. In the course of describing the future program at Fermilab, I will show how well it is aligned with the priorities articulated in the HEPAP report.

The Coming Revolution in Particle Physics

We are at the start of a revolution in our understanding of the nature of matter, energy, space, and time. We will soon be able to obtain experimental answers to questions that have shaped particle physics for decades. These answers will lead to a new and deeper understanding of the world around us, an understanding that will revolutionize our view of the universe.

Fermilab's vision for its future is to be at the forefront of that scientific revolution. The laboratory will be the home for accelerator-based particle physics in the U.S., for American physicists working abroad at the world's highest energy accelerator, and for some of the most far-reaching experiments at the boundary of particle physics and cosmology.

At the start of *The Coming Revolution in Particle Physics,* the Long Range Planning Committee stated the timeless questions that have guided our field since its inception:
What is the universe made of?
What are the basic laws of nature?

The existing theory of particle physics is starting to give way to something new on several fronts. We do not know which discoveries will break through the present limits of our understanding, but we believe that the changes will be revolutionary, not evolutionary. We know the important questions to ask, even though we do not yet know what answer nature will give us. Some of these most important questions are (I follow the Quantum Universe in naming the major subfields.) :

Unified Forces Are there undiscovered principles of nature: new symmetries, new physical laws? What is dark energy? Are there extra dimensions of space? Do all of the forces become one? Answers to these questions will involve new forces and new particles, and perhaps the extra dimensions predicted by string theory. They might also explain the nature of the dark energy that drives the acceleration of the universe. Present results indicate that much of this will become apparent at colliders able to produce collisions with teraelectron-volt (TeV) energies.

The Particle World Why are there so many kinds of particles? What are neutrinos telling us?

Neutrino masses could be a window on a very high mass scale, many orders of magnitude beyond the energies accessible with colliders. What is dark matter, and how can we make it in the laboratory? The supersymmetric particles predicted in string theory could be the source of dark matter in the universe. If so, we can probably produce and observe them at colliders in the next few years. We also should be able to see evidence of the dark matter as we move through the sea of dark matter that envelops us.

The Birth of the Universe. How did the universe come to be? What happened to the antimatter? The big bang produced equal amounts of matter and antimatter, but some tiny asymmetry favoring matter led to the present universe. Studies of quarks and leptons may explain the cause of that asymmetry.

Fermilab Today

Fermilab is the largest laboratory in the United States dedicated to particle physics. The laboratory's scientific program is designed to address these key scientific issues. The Tevatron collider is the highest energy collider in operation and is the only facility in the world that can now address many of the central questions listed above. In addition, the accelerator complex supports the most diverse particle physics program of any laboratory in the country, a program that includes collider experiments, neutrino experiments, experiments with hadron beams, and experiments testing new accelerator and detector technologies.

About 3000 physicists do research with Fermilab facilities on the most compelling questions in particle physics:

Run II of the Tevatron Over 1500 particle physicists explore the unification of forces, the nature of dark matter, and the mysteries of antimatter using the CDF and D0 detectors at the Fermilab Tevatron. Measuring the mass of the top quark and the W boson more precisely at the Tevatron will probe whether the Standard Model is showing signs of the new physics ahead. The experiments are exploring new territory in the hunt for extra dimensions, supersymmetry and quark substructure.

Research at the Large Hadron Collider To continue exploring the new physics opening up at the energy frontier, U.S. physicists will use Fermilab as the home laboratory for research using the Large Hadron Collider (LHC) at CERN. Fermilab is the research center for the collaboration of 400 physicists from U.S. institutions looking for discoveries at the energy frontier with data from the CMS experiment at the LHC. It is also the host laboratory for the collaboration of accelerator physicists from three laboratories building accelerator technology for and doing accelerator research with the Large Hadron Collider.

Neutrino physics About 250 physicists conduct research at Fermilab using the only two neutrino beamlines operating in the U.S. The MiniBooNE experiment is looking for exotic neutrinos using a low-energy neutrino beam from the Fermilab Booster. The MINOS experiment, sited over 400 miles northwest of Fermilab in the Soudan mine in northern Minnesota, will measure the evolution of neutrinos produced by the Fermilab Main Injector. In addition, smaller experiments are being proposed to study nuclear structure with neutrinos, using both existing beams.

Particle Astrophysics Fermilab was the first particle physics laboratory to build a group exploring the exciting science at the convergence of particle physics and astrophysics. The laboratory builds and operates experiments for three large collaborations, whose membership totals about 650 scientists doing research in particle astrophysics. The Sloan Digital Sky

Survey, a continuing source of astronomical discoveries, has been used with WMAP to pin down the amount of dark matter and dark energy in the universe. The Cryogenic Dark Matter Search, operating in the Soudan mine, is the leading experiment in searching for direct evidence of the Dark Matter halo and its interactions with normal matter. The Auger Cosmic Ray Observatory, in the high Argentine desert, is the largest array of detectors in the world observing cosmic rays.

Quarks and Antimatter In 2009, the BTeV facility will take over the use of the Tevatron. BTeV will be the most advanced experiment on quark physics and matter-antimatter asymmetry and will provide data for over 200 physicists pursuing that physics. *The Quantum Universe* describes the unique contributions of BTeV to studies of all three of the major subfields above.

All of these experimental programs are unique, and all are recognized as essential components of the world program in particle physics. Fermilab is the leading U.S. laboratory studying unification with colliders and the only one studying neutrinos with accelerators.

Fermilab's leadership role The system of seven accelerators at Fermilab provides a uniquely diverse and flexible platform for doing experiments across the spectrum of particle physics. As a result, the array of experiments operating at the Fermilab accelerators covers the widest range of physics at any U.S. laboratory, and the community of scientists doing research with them is the largest. The collection of physicists, engineers, and technical staff who operate and improve the accelerator complex is an asset of incalculable value in planning the future. Finally, the large Fermilab site and its surroundings provide the best physical environment for building large new accelerators of any particle physics laboratory in the world. Fermilab is also a world-renowned center of research and development on accelerator technologies, such as superconducting magnets. For all of these reasons, Fermilab is and will remain the leading U.S. laboratory for hosting particle physics with accelerators. At the same time, all of the major future projects done at Fermilab will be done in collaboration with the international network of laboratories and institutes involved in particle physics.

Fermilab in 2010

By the year 2010, particle physics is likely to be in the midst of the revolution. New data from the LHC will show signs of whatever new physics – extra dimensions, supersymmetry, one or more Higgs bosons – shows up at the TeV mass scale. A new round of neutrino experiments will have completed the first major step in understanding the nature of neutrino mass. If dark matter is due to supersymmetric particles, we should have observed their interactions underground and produced them in colliders. All of these new discoveries and measurements will lead to a new round of experiments to understand the underlying physics.

While the LHC will represent the energy frontier in 2010, the Fermilab accelerator complex will remain a unique platform for particle physics experiments. Fermilab will continue to be responsible for a large fraction of the U.S. program in particle physics at this time, with a central role in three of the five major facilities operating in 2010 that are discussed in *The Quantum Universe*:

- The **LHC** will be addressing the most important questions in particle physics at the energy frontier, and Fermilab is the lead laboratory for the U.S. efforts on the CMS experiment and on the accelerator.
- The Fermilab experiment **BTeV**, operating at the Tevatron, will represent the flagship of the generation beyond the existing B-factories in exploring the physics of heavy quarks and the matter-antimatter asymmetry.

- A number of experiments, including **MINOS**, will be using the Fermilab neutrino beams to expand our understanding of neutrinos.

Fermilab will be also be host to a large part of the U.S. program in Particle Astrophysics. An expanded and upgraded CDMS experiment will extend its investigation of the nature of dark matter; the Auger cosmic ray observatory will start to operate a second array in North America, in addition to the one in Argentina. The Dark Energy Survey, based on a large new state-of-the-art camera built here at Fermilab and mounted on the telescope at Cerro Tololo, could be making first observations. Finally, Fermilab will be working with lead laboratory LBNL and other laboratories in building the Joint Dark Energy Mission.

In the next decade the particle physics facility most likely to make revolutionary discoveries is the LHC, and Fermilab will play a critical role in enabling U.S. scientists to take full advantage of it. Given worldwide networks and grid computing, particle accelerators and research centers no longer need to be sited together. The critical features for a world-leading research center on LHC physics are the power of the computing infrastructure, the expertise of the support staff, and the concentration of intellectual talent leading the research. As the center of research with hadron colliders for the last twenty years, Fermilab is in an ideal situation to maintain research leadership for U.S. particle physics in the LHC era.

For the LHC experiment CMS, the data will be taken at CERN but the American physicists plan to do most of their research closer to their home universities. This motivates us to establish the LHC Physics Center at Fermilab, which we are planning along with university physicists. The Center will allow American universities and laboratories to get full scientific benefits from the investments the U.S. is making in the LHC. U.S. accelerator physicists will also develop their expertise in forefront accelerator technology while improving the scientific power of the LHC as a result of the accelerator research program centered at Fermilab. The LHC-directed research effort at Fermilab will be as large as that associated with one of the two current Tevatron collider experiments.

Because the time scale for building major experimental facilities for particle physics is 5-10 years, the experimental program that will be operating in 2010 is already under construction. The last major component is BTeV, which the HEPAP subpanel P5 strongly endorsed last year, concluding, "P5 supports the construction of BTeV as an important project in the world-wide quark flavor physics area." BTeV was included as one of the first tier of facilities in the Office of Science's facilities plan and was listed as one of the major facilities in *The Quantum Universe.* BTeV will start taking data late in 2009 and will be a leading instrument for quark physics in the next decade.

The most important role for Fermilab will be preparing to build a new accelerator facility. The Fermilab Long-Range Planning Committee identified two alternative visions for Fermilab in the period 2010 to 2020, depending on the development of the linear collider, the next worldwide project for particle physics. I will discuss those accelerators in the next section.

Fermilab in 2020

The overarching vision for Fermilab in 2020 is that it will be the primary site for particle physics accelerators in the U.S.

The most favorable option for U.S. particle physics is the construction of a linear electron-positron collider with initial energy 0.5 TeV, built sometime in the decade 2011-2020. North

America, Europe and Japan have all identified this as the next big project for particle physics because of its unique ability to address the most important issues in the field. They have formed the beginning of a collaboration to create an international laboratory of a novel type. The global linear collider laboratory would be funded and managed jointly by national laboratories and their funding agencies in the U.S., Europe and Japan. The countries are not interested in funding a new permanent laboratory in addition to the existing national ones, so it is imperative that the plan make optimum use of the assets residing in the present laboratories.

A critical element in planning the linear collider is choosing a site that is geologically suitable, located on or under available land, and at or very close to an existing particle physics laboratory that serves as host. During the long period of building up the infrastructure at the linear collider site, it is critical that staff can shuttle between work at the host laboratory and at the linear collider on a daily basis. Another requirement is the availability of up to 500 MW electrical power at an affordable cost. The best site in the world, given all of these constraints, is one within 25 miles of Fermilab. Whether the linear collider is sited in the U.S., and specifically in northern Illinois, will be a decision taken at the highest level of several governments. From technical and project cost perspectives, however, the best site is near Fermilab; and everything should be done to promote such a solution. Fermilab has therefore launched an effort to develop in detail all of the information needed to support a bid to host the linear collider there.

The physics of the linear collider will be whatever the revolutionary new physics turns out to be. Whether it is supersymmetry, extra dimensions, or some other extension of the Standard Model of particle physics, the linear collider will provide a completely new type of instrument to explore the new territory. Just as the cosmic microwave background and distant supernovae provide completely different measurements needed to understand the contributions of dark matter and dark energy to the energy budget of the universe, so the linear collider will provide different insights from those provided by the LHC. They may also provide indirect evidence of new physics that might come from dark matter searches or decays of B mesons.

Wherever the linear collider is built, the model will be quite different from earlier accelerator projects. Several laboratories around the world will build major components of the accelerator complex and the detector, in addition to making intellectual contributions to the design. As a result, the role of the host laboratory will not be as all-encompassing as it is for the LHC or the Tevatron. Of course, the linear collider would be the largest effort at Fermilab, as it would be for the other laboratories. But Fermilab could not and should not abandon its other critical roles such as its host role for the US part of the CMS collaboration, which will still be very active and producing great physics in 2020.

Because neither the siting nor the timing of the linear collider in the U.S. is certain, the Fermilab Long-Range Planning Committee has developed an alternative vision for what accelerators are operating in the future in the U.S., using the assumption of an offshore linear collider is as a model. In this vision, the most exciting physics opportunity that can be addressed with a national, rather than international, facility is neutrino physics.

The neutrino experiments that might be operating by 2015 include, besides MINOS, a shorter-baseline experiment at the Japanese J-PARC facility, a possible second experiment using the Fermilab neutrino beam, and a possible experiment built at a reactor. Although we will know from these experiments far more about neutrinos, the least understood particles of any that we have yet seen, it is overwhelmingly likely that a more powerful experiment will be needed to explore the possibility of CP violation in neutrinos, the matter-antimatter asymmetry that could explain the survival of matter from the early universe until today.

To follow the path of neutrino discovery will take larger experiments and more intense neutrino beams than any being built today. The NuMI neutrino beam and the MINOS experiment will start operating in early 2005. They will form the basis of a series of steps along the path of discovery, each one designed to take best advantage of what is learned earlier. The next step could be a larger experiment built off the axis of the NuMI beam line, coupled with some modest intensity upgrades to the accelerator complex.

The biggest step in the future of neutrinos at Fermilab would be a low-energy (8 GeV) but high-intensity proton driver, capable of producing 2 Megawatts of beam power at 8 GeV and, with the existing Main Injector, 2 Megawatts of beam power at 150 GeV. Such a project would be roughly as large as the Main Injector construction project. The technical design of the Proton Driver will be complete around 2007-8. If the linear collider were not about to start construction at Fermilab by that time, the particle physics community would give a strong push toward building the Fermilab Proton Driver, ensuring a future for neutrino discovery physics that would last until 2020.

In summary, there are two alternatives for U.S. particle physics and for Fermilab in 2020. In the first, preferred scenario, Fermilab would be the host of an international linear collider in northern Illinois, in which several laboratories around the world would be major stakeholders. Physics at the linear collider would be the largest research activity at the laboratory. There would also be continuing research at Fermilab on LHC physics, particle astrophysics, and neutrino physics, following the evolution of those fields based on the discoveries of the previous decade.

In the second scenario, in which there is no linear collider built in the U.S., Fermilab would develop its unique set of accelerators further, making it once again into the world's leading instrument for neutrino physics. A series of upgrades to the present accelerators and detectors would be needed, with the Proton Driver as the single largest step. Fermilab would continue its role in LHC physics and particle astrophysics. It would also have a role in the linear collider somewhat similar to its present role in the LHC.

In either case, Fermilab would be the U.S. site for accelerators operating at the forefront of particle physics. The largest facilities, the LHC and the linear collider, would be operating as international science enterprises, involving all of the major particle physics laboratories around the world.

The discoveries of the coming decade will significantly clarify the detailed picture of U.S. particle physics twenty years from now. The physics program in 2020 and beyond will be shaped by all that we learn about the physics of the universe between now and 2010.

What we need to do now

There are several things we need to do now to realize the opportunities for discovery in the next decade and to be ready to build the facilities needed for the discoveries in the decade after that. Some of these we have already been doing.

- **Continue to push Run II physics to its limits over the next few years**. Nothing could advance the field more than a first discovery of dramatically new physics at the energy frontier with CDF and D0. We have a well-thought-out plan to optimize the physics from Run II, and a new round of exciting results will be coming out every year.
- **Provide more protons for the neutrino program.** Neutrino experiments can always make good use of more protons, and we are taking steps to increase proton intensity to

the limits of the present set of accelerators. The Accelerator Division is developing a plan for improvements in the next few years, and we are also looking at major upgrades that could be done before the Proton Driver is ready for construction.

- **Start construction of the BTeV project.** We have established the project office and are working with them to develop the baseline cost and schedule and to obtain the many approvals needed to begin the project.

In other areas, we are following the recommendations of the Long Range Planning Committee on how to build for the future.

- **Grow the research effort on the linear collider, on both the accelerator and detector fronts, and do detailed studies of nearby sites.** I have written a letter to the leader of the linear collider R&D team asking him to develop plans to expand the effort at Fermilab, no matter which of the new technologies is chosen later this year. I also asked him to develop a site plan appropriate for a host laboratory. In addition, we are putting together a bid to host the central design team that will lead the technical design of the linear collider.
- **Advance the design of a Proton Driver and develop fully the physics case for it.** I have appointed leaders of the Proton Driver effort and asked them to lead a team to accomplish these goals. The immediate goals are to develop and document the physics case, establish documentation of mission need, prepare cost estimates for the linac and synchrotron options, and to examine siting issues.
- **Build up the CMS research program at Fermilab, including the LHC Physics Center.** I have written a letter to the leaders of the CMS research effort committing the laboratory to building up the LHC Physics Center and asking them to get it started quickly. I also have written a letter to members of the CMS collaboration announcing the steps we were taking to establish the LPC and announced it in Fermilab Today.
- **Establish a Center for Particle Astrophysics at Fermilab.** I am establishing this center to serve as the intellectual center for research at the laboratory related to astrophysics. We will locate the various groups working in this area of physics together.

For U.S. physicists to be at the forefront of the coming revolution in particle physics, Fermilab should lead the way and it is our plan to do so.