The State of Particle Physics in our Nation

Testimony to the Subcommittee on Energy and Environment of the
House of Representatives Committee on Science and Technology
Hearing on *"Finding the Building Blocks of the Universe"*
Piermaria J. Oddone, Director Fermilab
October 1, 2009

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Today I will describe the state of my field of research, high-energy particle physics. Before examining the major questions in particle physics, I would like to start with a personal note. I was born in Peru and grew up far away from any possibilities of doing this kind of research. In high school, reading about the amazing discoveries and pace of research in nuclear physics and beyond, I was attracted to physics and proposed to my parents that I become a physicist. This was, for them, a very strange notion. The beacon for the world in this kind of research at the time was the United States. My parents had the wisdom to ship me to the US to study physics at MIT. Today I am honored to come before you after nearly five decades of witnessing, participating in and benefiting from the fantastic research opportunities in our country that have been made possible by federal support of discovery science in particle physics.

Particle physics has never been more exciting. Experiments at the Tevatron collider at Fermilab and soon at the Large Hadron Collider at the European particle physics laboratory CERN are closing in on the elusive particle – the Higgs boson -- that we believe endows elementary particles with their mass. But in addition we may find something even more astonishing: that for every particle known today, a new and previously unseen twin exists, heavier and spinning in a different way. This discovery would herald a new understanding of space-time and the Theory of Relativity. Furthermore, several generations of experiments using accelerators, reactors, the sun and cosmic rays are advancing our understanding of neutrinos, elusive particles that, together with their heavy counterparts yet to be discovered, may be responsible for the matter in our universe.

In the last five decades we have moved from a complete lack of understanding of the bewildering variety of newly discovered particles to a remarkable understanding of how all of these hundreds of particles fit together in a simple and beautiful framework. This modestly named "Standard Model" has produced a transformation of how we think of the universe: how it began and our place within it. This remarkable intellectual achievement is the result of a powerful interplay between theorists and the experimental physicists and engineers that have built some of the most technologically advanced facilities ever created. The Standard Model has only four fundamental forces and only a few elementary constituents, namely, six quarks and six leptons. At the same time that we have made discoveries that confirm this simple conceptual paradigm, we are discovering a growing number of profound mysteries that cannot be resolved within it. One can say that our progress has been as great in expanding what we know as in expanding our awareness of a vast landscape we know nothing about.

As we have advanced in our understanding of particle physics, we have discovered the deep connection between the world of the very small that we study with accelerators and the world of the very large that we observe in the cosmos. The largest objects in the universe, galaxies and cluster of galaxies, originated in the subatomic quantum fluctuations in the earliest moments of the universe. Many of the mysteries that confront us, such as the discovery of dark matter and dark energy as primary components of our universe, or the nature of neutrinos and their transformations, cannot be explained within our current understanding of particles and forces, and yet such explanations must exist. This tension between what we have observed and what we can explain is driving theorists to develop many alternative frameworks to account for these phenomena. A great expansion of our experimental horizons will soon take place with the start of the Large Hadron Collider (LHC) in Geneva, Switzerland. The LHC promises an extraordinarily exciting and productive period in the world of science as these theories confront experimental reality and we make new discoveries, perhaps beyond anything so far imagined.

The extreme technical demands of particle physics experiments lead to inventions of unanticipated utility. Many innovations have come out of the development of accelerators, fast computational techniques, data mining and processing and particle detector technologies as described more extensively in Appendix 3. These innovations benefit society and the economy, such as

1) nuclear medicine and the use of isotopes for treatment and for metabolic studies;
2) the use of accelerators in proton and neutron cancer therapies;
3) the development of light sources and neutron sources to advance many fields of science, including materials science, atomic and molecular science, chemical sciences, nanosciences and biosciences;
4) industrial accelerators to sterilize food, modify materials, or inspect components;
5) radiation detectors used in scanning applications for medical diagnosis;
6) radiation detectors for national security and other detection purposes;
7) development of advanced computer technology, spurred by early application of computers for particle physics data-taking, pattern recognition and analysis on a massive scale
8) new massive computer architectures, inspired by the boundless needs for computational power for quantum chromodynamics calculations;
9) advance of the greatest distributed computing systems in the world, grid computing, launched by the need for computational resources to mine and model data;
10) perhaps the best known example of an application of particle physics technology, the creation of the World Wide Web at CERN, the European particle physics laboratory. Impelled by the need for communications across continents on many different platforms, US particle physics laboratories quickly followed – and so did the world;
11) Future applications of accelerator technologies: safer sub-critical nuclear reactors, transmutation of nuclear waste; bench top accelerators for material, chemical and biological research.

Research in particle physics plays an important role in science, technology, engineering and mathematics (STEM) education. Making discoveries about the world around us has excited humankind for centuries. The real possibility of understanding matter, energy, space and the evolution and fate of the universe generates excitement around the globe; it is a strong driver of scientific exploration, and it attracts young people to science. For those who choose to pursue particle physics, our discipline prepares students not only for careers in particle physics but for any career in which large, multidisciplinary teams tackle complex scientific and technological problems. Federal support of particle physics research has trained thousands of scientists. At my institution, Fermilab, alone, more than 1700 young scientists have received their Ph.D.s in the last three decades.

The field has become progressively more international, demanding new forms of cooperation between the world agencies that support science. As more countries have invested in particle physics research the scientific collaborations to build accelerators and large detector facilities can typically involve dozens of countries and more than a hundred institutions. Coordination on a global scale is now common and will become more so in the future. The US position in this global context of scientific cooperation and diplomacy is changing. We have been very much at the leading edge, attracting large investment from global partners to the US. For example, the groups operating the CDF and DZERO detectors in the Tevatron, Fermilab's proton-antiproton particle collider, each have hundreds of physicists. About 40% of these physicists hail from dozens of countries beyond our shores, bringing their resources and knowledge to the US. Similarly, nearly half of the support for BaBar, the detector in the Asymmetric B-factory at SLAC, came from Europe. In a reversal of flow, today nearly 1500 physicists from the US participate in LHC experiments in Europe, roughly 25% of all users of that facility.

The free international sharing of facilities that has characterized our field has long been dependent on a balance of investments by various countries and regions over time, primarily by Europe and the US but also with significant investments by Japan and China. Today, however, there is a growing imbalance that should raise grave concern. While the US has either been the leader in particle physics research or shared leadership with Europe, that leadership is about to pass wholly to Europe with the start-up of the LHC. Europe's annual investment in particle physics is at least twice as large as that in the US. The capital value of their facilities will exceed that of the US by an order of magnitude when the Tevatron shuts down. Nearly all major US facilities, the Asymmetric B-factory at SLAC, the Tevatron at Fermilab, the CESR collider at Cornell and the AGS at Brookhaven have either been shut down for particle physics research or will be shut down within two years. The last upgrade to a particle physics accelerator facility in the US was the construction of the Main Injector at Fermilab, completed ten years ago, in 1999. It will be the one remaining facility devoted to particle physics in the US once the Tevatron shuts down, and it will have strong competition from an advanced new facility starting in Japan at JPARC.

The future for discovery science in particle physics in the US will depend critically on following a clear scientific roadmap that establishes pioneering research facilities to replace our aging facilities. Last year the High Energy Physics Advisory Committee, or HEPAP, developed a comprehensive plan for the field. This plan can be funded within the resources anticipated for the Office of Science during the next decade. It contains a set of balanced investments in the three great lines of inquiry of particle physics, all of them driving toward a unified understanding of nature:

1) The *Energy Frontier,* where we directly produce new particles and explore new phenomena;
2) The *Intensity Frontier*, where neutrinos and rare particle processes tell us indirectly about new phenomena at energies even beyond the LHC; and
3) The *Cosmic Frontier*, where we study natural phenomena arising from the early universe that ultimately will connect to our understanding of particles and forces.

The executive summary of this HEPAP plan "US Particle Physics: Scientific Opportunities" is included in this testimony as Appendix 2. Support for the HEPAP plan at the three frontiers is essential for a vigorous world-leading program in particle physics. And a vigorous and healthy program in this fundamental field of science is essential for us as a nation to derive the practical benefits that come from pushing the boundaries of science and technology, to provide a beacon for scientists and students from the US and the world and to continue as the leader in discovery science.

Appendix 1

The Major Questions in Particle Physics

Appendix 2

“US Particle Physics: Scientific Opportunities”

Chapter 1: Executive Summary

Appendix 3

“US Particle Physics: Scientific Opportunities”

Chapter 2: Particle Physics in the National and International Context

2.1 Long-Term Value of Research in Fundamental Sciences

2.2 Benefits to Society

2.3 The International Context

Appendix 4

Short Biography of Piermaria Oddone

Appendix 1

The Major Questions in Particle Physics

The Standard Model Framework has transformed the way we look at the world around us. It encompasses the forces and particles that we are familiar with, from nuclei to atoms to chemistry to biology. We used to think this was what the world is made of. Today, we know better: it is only some 5% of the matter and energy in the universe. The vast majority of the universe is dark matter and dark energy, still totally mysterious and detected only through their gravitational effects on the cosmos. Observations in space, deep underground and, most powerfully, in experiments at particle accelerators will ultimately reveal the particles and forces that underlie dark matter and dark energy.

Profound question such as these arise when we confront the Standard Model with observations of the universe around us and fail to find an answer within it. It is clearly an incomplete framework that must be radically expanded to bring a unified understanding of nature

Some of the questions that arise when we confront the Standard Model with cosmological observations are:

- What is the nature of dark matter? Is it a simple particle or a complex set of particles and interactions?
- What is the nature of dark energy?
- Why is the universe we see made out of matter and not equal parts of matter and anti-matter as the Standard Model would have it? Do neutrinos provide the answer?
- What new forces acted at the Big Bang to produce the distribution of matter we see today?
- How will the universe evolve and what is its end-point?

Other profound questions arise when we join the Standard Model with gravitation:

- Do all forces unify in a single framework?
- Are there extra dimensions of space?
- Are there hidden sectors not yet observed because they are too massive or because they interact weakly with our world?

Further questions arise from the Standard Model itself:

- What mechanism endows elementary particles, those without any internal structure, with mass?
- Does the Higgs particle that theoretically endows elementary particles with mass actually exist?
- What is the nature of neutrinos and what do their tiny masses and transformations tell us?

- Do heavy neutrinos exist in the early universe and explain how matter came to dominate?
- Why are there three families of similar elementary particles and not some other number: two or four or more?
- Why is there such a vast difference in the masses of the quarks, a factor greater than 10,000, from the quarks that make up the proton to the top quark?
- Why are the neutrino masses so light, a million times smaller than the electron mass?

These questions sound almost theological. It is a feature of the remarkable age of experimentation and discovery we live in that we can expect to answer many of them in the next few decades.

Further Reading:

1) National Academy of Sciences Report " Connecting Quarks to the Cosmos: Eleven Science Questions for the New Century", (http://www.nap.edu/openbook.php?isbn=0309074061)

2) National Academy of Sciences Report " Revealing the Hidden Nature of Space and Time: Charting a Course for Elementary Particle Physics" (http://www.nap.edu/catalog/11641.html)

Appendix 2

A US Roadmap for Particle Physics

The field is currently progressing along the roadmap of the Particle Physics Project Prioritization Panel whose May, 2008 report was recommended by the High Energy Advisory Committee and serves as a guide: "US Particle Physics Opportunities: A Strategic Plan for the Next Ten Years" (http://www.er.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf). The Panel was convened at the request of the DOE and the NSF to produce a realistic plan for particle physics under several budget scenarios. This plan proposes to develop the three frontiers of particle physics in a balanced way and has replaced the previous DOE strategy that was aimed at hosting the International Linear Collider early in the next decade. The reason for the changed strategy was the large cost estimate for the International Linear Collider and the absence of new information on the required energy scale – something that only research at the LHC will provide. The cost estimate for the International Linear Collider was developed rigorously by the world particle physics community and it allowed our policy makers to determine that such a plan could not be realized any time soon and that a new strategy was required for the health of the field inthe US.

One important aspect of this plan is the need for cooperation in major projects across government agencies. The planned Joint Dark Energy Mission requires a strong partnership between the DOE and NASA. The development of the world-leading neutrino program in the US with a new beam from Fermilab aimed at the Deep Underground Science and Engineering Laboratory at the Homestake mine, South Dakota, 1300 km away, requires a strong partnership between the DOE and the NSF. While partnerships between NASA and DOE have been successful in the past such as in the case of the Fermi satellite, and partnerships between the DOE and NSF have been successful such as in the case of LHC, these new projects are much larger and will demand even closer collaboration.

In the section below I reproduce in its entirety the Executive Summary of the Particle Physics Project Prioritization Panel: "US Particle Physics Opportunities: A Strategic Plan for the Next Ten Years"**.**

1 EXECUTIVE SUMMARY

Particle physics is a central component of the physical sciences, focused on the fundamental nature of matter and energy, and of space and time. Discoveries in this field, often called high-energy physics, will change our basic understanding of nature. The Standard Model of particle physics provides a remarkably accurate description of elementary particles and their interactions. However, experiment and observation strongly point to a deeper and more fundamental theory that breakthroughs in the coming decade will begin to reveal.

To address the central questions in particle physics, researchers use a range of tools and techniques at three interrelated frontiers:

- The Energy Frontier, using high-energy colliders to discover new particles and directly probe the architecture of the fundamental forces.

- The Intensity Frontier, using intense particle beams to uncover properties of neutrinos and observe rare processes that will tell us about new physics beyond the Standard Model.

- The Cosmic Frontier, using underground experiments and telescopes, both ground and space based, to reveal the natures of dark matter and dark energy and using high-energy particles from space to probe new phenomena.

As described in the box on pages 9-11, these three frontiers 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 ultimately aim at the same transformational science.

The changing context

Recent reports, including the National Research Council's “Revealing the Hidden Nature of Space and Time” (the EPP2010 report) and earlier P5 reports, have discussed the outlook for the field of particle physics in the United States. The scientific priorities have not changed since those reports appeared, but the context for the scientific opportunities they describe has altered.

Particle physics in the United States is in transition. Two of the three high-energy physics colliders in the US have now permanently ceased operation. The third, Fermilab's Tevatron, will turn off in the next few years. The energy frontier, defined for decades by Fermilab's Tevatron, will move to Europe when CERN's Large Hadron Collider begins operating. American high-energy physicists have played a leadership role in developing and building the LHC program, and they constitute a significant fraction of the LHC collaborations—the largest group from any single nation. About half of all US experimental particle physicists participate in LHC experiments.

As this transition occurs, serious fiscal challenges change the landscape for US particle physics. The large cost estimate for the International Linear Collider, a centerpiece of previous reports, has delayed plans for a possible construction start and has led the particle physics community to take a fresh look at the scientific opportunities in the decade ahead. The severe funding reduction in the Omnibus Bill of December 2007 stopped work on several projects and had damaging impacts on the entire field. The present P5 panel has developed a strategic plan that takes these new realities into account.

Overall recommendation

Particle physics explores the fundamental constituents of matter and energy and the forces that govern their interactions. Great scientific opportunities point to significant discoveries in particle physics in the decade ahead.

Research in particle physics has inspired generations of young people to engage with science, benefiting all branches of the physical sciences and strengthening the scientific workforce. To quote from the EPP2010 report:

> *“A strong role in particle physics is necessary if the United States is to sustain its leadership in science and technology over the long term.”*

The present P5 panel therefore makes the following overall recommendation:

> **The panel recommends that the US maintain a leadership role in world-wide particle physics. The panel recommends a strong, integrated research program at the three frontiers of the field: the Energy Frontier, the Intensity Frontier and the Cosmic Frontier.**

The Energy Frontier

Experiments at energy-frontier accelerators will make major discoveries about particles and their interactions. They will address key questions about the physical nature of the universe: the origin of particle masses, the existence of new symmetries of nature, the existence of extra dimensions of space, and the nature of dark matter. Currently, the Tevatron at Fermilab is the highest-energy collider operating in the world.

> **The panel recommends continuing support for the Tevatron Collider program for the next one to two years, to exploit its potential for discoveries.**

In the near future, the Large Hadron Collider at CERN in Geneva, Switzerland will achieve much higher collision energies than those of any previous accelerator, to explore the energy range we call the Terascale. The LHC represents the culmination of more than two decades of international effort and investment, with major US involvement. Experiments at the LHC are poised to make exciting discoveries that will change our fundamental understanding of nature. Significant US participation in the full exploitation of the LHC has the highest priority in the US high-energy physics program.

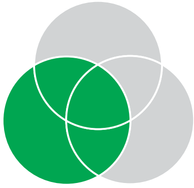
> **The panel recommends support for the US LHC program, including US involvement in the planned detector and accelerator upgrades.**

The international particle physics community has reached consensus that a full understanding of the physics of the Terascale will require a lepton collider as well as the LHC. The panel reiterates the importance of such a collider. In the next few years, results from the LHC will establish its required energy. If the optimum initial energy proves to be at or below approximately 500 GeV, then the International Linear Collider is the most mature and ready-to-build option with a construction start possible in the next decade. A requirement for initial energy much higher than 500

GeV will mean considering other collider technologies. The cost and scale of a lepton collider mean that it would be an international project, with the cost shared by many nations. International negotiations will determine the siting; the host will be assured of scientific leadership at the energy frontier. Whatever the technology of a future lepton collider, and wherever it is located, the US should plan to play a major role.

For the next few years, the US should continue to participate in the international R&D program for the ILC to position the US for an important role should the ILC be the choice of the international community. The US should also participate in coordinated R&D for the alternative accelerator technologies that a lepton collider of higher energy would require.

> **The panel recommends for the near future a broad accelerator and detector R&D program for lepton colliders that includes continued R&D on ILC at roughly the proposed FY2009 level in support of the international effort. This will allow a significant role for the US in the ILC wherever it is built. The panel also recommends R&D for alternative accelerator technologies, to permit an informed choice when the lepton collider energy is established.**



The Intensity Frontier

Recent striking discoveries make the study of the properties of neutrinos a vitally important area of research. Measurements of the properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for the evolution of the universe. The latest developments in accelerator and detector technology make possible promising new scientific opportunities in neutrino science as well as in experiments to measure rare processes. The US can build on the unique capabilities and infrastructure at Fermilab, together with DUSEL, the Deep Underground Science and Engineering Laboratory proposed for the Homestake Mine in South Dakota, to develop a world-leading program of neutrino science. Such a program will require a multi-megawatt-powered neutrino source at Fermilab.

> **The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL and a high-intensity neutrino source at Fermilab.**
>
> **The panel recommends an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technologies for a large multi-purpose neutrino and proton decay detector.**

Construction of these facilities could start within the 10-year period considered by this report.

A neutrino program with a multi-megawatt proton source would be a stepping stone toward a future neutrino source, such as a neutrino factory based on a muon storage ring, if the science eventually requires a more powerful neutrino source. This in turn could position the US program to develop a muon collider as a long-term means to return to the energy frontier in the US.

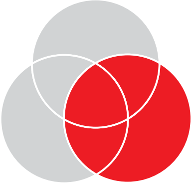
The proposed DUSEL is key to the vision for the neutrino program. It is also central to nonaccelerator experiments searching for dark matter, proton decay and neutrinoless double beta decay. DOE and NSF should define clearly the stewardship responsibilities for such a program.

> **The panel endorses the importance of a deep underground laboratory to particle physics and urges NSF to make this facility a reality as rapidly as possible. Furthermore the panel recommends that DOE and NSF work together to realize the experimental particle physics program at DUSEL.**

Scientific opportunities through the measurement of rare processes include experiments to search for muon-to-electron conversion and rare-kaon and *B*-meson decay. Such incisive experiments, complementary to experiments at the LHC, would probe the Terascale and possibly much higher energies.

> **The panel recommends funding for measurements of rare processes to an extent depending on the funding levels available, as discussed in more detail in Sections 3.2.2 and 7.2.3.**

The Cosmic Frontier



Although 95 percent of the universe appears to consist of dark matter and dark energy, we know little about either of them. The quest to elucidate the nature of dark matter and dark energy is at the heart of particle physics—the study of the basic constituents of nature, their properties and interactions.

The US is presently a leader in the exploration of the Cosmic Frontier. Compelling opportunities exist for dark matter search experiments, and for both ground-based and space-based dark energy investigations. In addition, two other cosmic frontier areas offer important scientific opportunities: the study of high-energy particles from space and the cosmic microwave background.

> **The panel recommends support for the study of dark matter and dark energy as an integral part of the US particle physics program.**
>
> **The panel recommends that DOE support the space-based Joint Dark Energy Mission, in collaboration with NASA, at an appropriate level negotiated with NASA.**
>
> **The panel recommends DOE support for the ground-based Large Synoptic Survey Telescope program in coordination with NSF at a level that depends on the overall program budget.**
>
> **The panel further recommends joint NSF and DOE support for direct dark matter search experiments.**
>
> **The panel recommends limited R&D funding for other particle astrophysics projects and recommends establishing a Particle Astrophysics Science Advisory Group.**

Enabling technologies

The US must continue to make advances in accelerator and detector R&D to maintain leadership at the Intensity and Cosmic Frontiers of particle physics; to allow for a return to the Energy Frontier in the US; and to develop applications for the benefit of society.

> **The panel recommends a broad strategic program in accelerator R&D, including work on ILC technologies, superconducting rf, high-gradient normal-conducting accelerators, neutrino factories and muon colliders, plasma and laser acceleration, and other enabling technologies, along with support of basic accelerator science.**

The panel recommends support for a program of detector R&D on technologies strategically chosen to enable future experiments to advance the field, as an essential part of the program.

Benefits to society

The drive to understand the world around us is a basic part of our humanity. Research in fundamental science provides the ideas and discoveries that form the long-term foundation for science and technology as a whole, which in turn drive the global economy and our very way of life. Each generation of particle accelerators and detectors builds on the previous one, raising the potential for discovery and pushing the level of technology ever higher. From the earliest days of high energy physics in the 1930s to the latest 21st-century initiatives, the bold and innovative ideas and technologies of particle physics have entered the mainstream of society to transform the way we live. Section 2 addresses these benefits in more detail.

Unique to particle physics is the scale of the science: the size and complexity not only of accelerators and detectors but also of scientific collaborations. For example, superconducting magnets existed before Fermilab's Tevatron accelerator, but the scale of the accelerator made the production of such magnets an industrial process, which led to cost-effective technology for magnetic resonance imaging. The World Wide Web was invented to solve the problem of communicating in international collaborations of many hundreds of physicists. The scale on which particle physicists work results in innovations that broadly benefit society.

Particle physics has a profound influence on the workforce. The majority of students trained in particle physics find their way to diverse sectors of the national economy such as national defense, information technology, medical instrumentation, electronics, communications, transportation, biophysics and finance—wherever the workforce requires highly developed analytical and technical skills, the ability to work in large teams on complex projects, and the ability to think creatively to solve unique problems.

The international context

The scientific opportunities provided by particle physics bring together scientists from every corner of the globe to work together on experiments and projects all over the world. Both the technical scale and the costs of today's largest accelerators and experiments put them beyond the reach of any single nation's ability to build or operate. Particle physics projects now take shape as international endeavors from their inception. As the costs and scale of particle physics facilities grow, international collaboration becomes increasingly important to the vitality of the field. Global cooperation, a hallmark of particle physics research, will be even more important in the future.

The Large Hadron Collider accelerator and detector system, for example, drew from innovation and expertise in Europe, the Americas and Asia to deliver the cutting-edge technology required for this next-generation collider program. The proposed LHC upgrades will likewise have continuing and very significant contributions from these regions. The successful programs at the KEK and SLAC *B* factories and at the Tevatron provide additional examples of the benefits of international collaboration. These scientific collaborations take on new significance as beacons for free and open exchange among men and women of science of all nations. They offer an inspiring model for cooperation from a field long known for its leadership in international collaboration.

As particle physics moves into the future, the balance of the physical location of the major facilities among the regions of the world will be key to maintaining the vitality of the field in each region and as a whole. In developing a strategic plan for US particle physics, the P5 panel kept the international context very much in mind.

The funding scenarios

The funding agencies asked the panel to develop plans in the context of several DOE funding scenarios:

A. Constant level of effort at the FY2008 funding level
B. Constant level of effort at the FY2007 funding level
C. Doubling of budget over ten years starting in FY2007
D. Additional funding above the previous level, associated with specific activities needed to mount a leadership program

The FY2007 DOE funding level was $752M; the FY2008 level was $688M. Constant level of effort here means that the budget increases with inflation in then-year dollars. The panel also received guidance on NSF budget assumptions. Interagency collaboration on particle physics experiments has become increasingly important. The plan presented in this report depends on such collaborative funding among DOE, NSF and NASA.

The panel evaluated the scientific opportunities for particle physics in the next 10 years under the various budget scenarios.

Scenario B: Constant level of effort at the FY2007 level

The scenario of constant level of effort at the FY2007 level, Scenario B, would support major advances at all three interrelated frontiers of particle physics. At the Energy Frontier, the Fermilab Tevatron would run in 2009, but the planned run in 2010 to complete the program could not take place due to budgetary constraints. The LHC experiments would be well under way. These experiments will likely make significant discoveries that could change our fundamental understanding of nature. R&D would go forward on future lepton colliders. At the Intensity Frontier, the MINOS, Double Chooz, Daya Bay and NOvA experiments would yield a greatly improved—if not complete—understanding of the fundamental properties of neutrinos. Precision measurements, limited to a muon-to-electron conversion experiment, would be carried out and the US would participate in one offshore next-generation *B* Factory. On the Cosmic Frontier, greatly improved measurements shedding light on the nature of dark energy would come from the DES, JDEM and LSST projects. The next generation of dark matter search experiments would reach orders-of-magnitude greater sensitivity to—perhaps even discover—particles that can explain dark matter.

Under Scenario B, the US would play a leadership role at all three frontiers. Investments in accelerators and detectors at the LHC would enable US scientists to play a leading role in the second generation of studies at the Energy Frontier. Investments in facility capabilities at the Intensity Frontier at Fermilab and DUSEL would allow the US to be a world leader in neutrino physics in the following decade. Funding of the cutting edge experiments studying dark matter and dark energy would insure continued US leadership at the Cosmic Frontier. Investments in a broad strategic accelerator R&D program would enable the US to remain at the forefront of accelerator developments and technologies focused on the needs of the US program at the Energy and Intensity Frontiers.

Scenario A: Constant level of effort at the FY2008 level

Budget Scenario A would significantly reduce the scientific opportunities at each of the three frontiers compared to Scenario B over the next 10 years. It would severely limit scientific opportunities at the Intensity Frontier during the next decade. Scenario A would require canceling planned experiments and delaying construction of new facilities. It would slow progress in understanding dark energy at the Cosmic Frontier and R&D toward future accelerator facilities at the Energy Frontier. It would cut the number of scientists, as well as graduate students and postdoctoral fellows. Scenario A would unduly delay projects, extending them over a longer period.

Scenario A would most profoundly limit studies at the Intensity Frontier, with a negative impact on both neutrino physics and high-sensitivity measurements. It would require cancellation of the NOvA neutrino experiment that is ready for construction. The MINERvA experiment could not run beyond FY2010 due to lack of funds to operate the Fermilab accelerator complex. Consequently, a first look at the neutrino mass hierarchy would be unlikely during the next decade, and experimenters could not measure neutrino cross sections, including those important to future long-baseline neutrino oscillation experiments. The US could not contribute significantly to the next-generation overseas *B* factories that will carry out unprecedented studies of matter-antimatter asymmetry and searches for new processes in the quark sector. Furthermore, this budget scenario would delay the construction of a high-intensity proton source at Fermilab by at least three to five years. This delay would in turn severely compromise the program of neutrino physics and of high-sensitivity searches for rare decays at the Intensity Frontier in the subsequent decade.

For dark-energy studies at the Cosmic Frontier, Budget Scenario A would delay DOE funding for the ground-based LSST telescope.

This budget scenario could not support the investment in new facilities for advanced accelerator R&D, important for future accelerators both at the energy frontier and for other sciences. As discussed above, it would also delay the construction of a high-intensity proton source, postponing the establishment of a foundation for energy frontier studies at a possible future muon collider.

Scenario A would require an additional reduction of approximately 10 percent beyond the FY2008 cuts in the number of scientists over the 10-year period. It would lead to a significant drop in the number of graduate students and postdoctoral fellows. Scenario A's drought in R&D coupled with delays in facility construction imposed during this decade would limit scientific opportunities in the subsequent decade.

Overall, while this funding level could deliver significant science, there would be outstanding scientific opportunities that could not be pursued. It would sharply diminish the US capability in particle physics from its present leadership role.

Scenario C: The doubling budget

Budget Scenario C would support a world-class program of scientific discovery at all three frontiers in the decade ahead. It would provide strong support for the development of future research capabilities and of the scientific work force. Programs could move forward at a more efficient pace, with reduced costs, more timely physics results and increased scientific impact.

At the Energy Frontier, this budget scenario would extend the discovery potential of the Fermilab Tevatron Collider by supporting operation in FY2010. Budget scenario C would provide robust funding for exploitation of the LHC physics potential. It would increase operations funding for US groups working in Europe on the LHC and provide the needed personnel support at both universities and national laboratories for LHC detector and machine upgrades.

Progress toward a future lepton collider is a very high priority of the field worldwide. Should results from the LHC show that the ILC is the lepton collider of choice, funding in this scenario would support R&D and enable the start of construction of an ILC abroad. If LHC results point to another lepton collider technology, its R&D would advance. Increased funding for muon collider R&D would lead to an earlier feasibility determination for a neutrino factory and perhaps a muon collider.

Scenario C would significantly advance the exploration of physics at the Intensity Frontier. Construction of a new high-intensity proton source at Fermilab, which would support both neutrino physics and precision searches for rare decays, would be complete. Scenario C would enable an earlier construction start than would Scenario B and would shorten the construction time. It would also advance the design and construction of a beamline to DUSEL and would reduce the overall cost and risk of both these projects. Efforts to develop the technology for large-scale liquid argon or water Cerenkov detectors for neutrino physics and proton decay would benefit greatly from increased funding, leading to an earlier construction start, shorter construction period and reduced risk for a large underground detector at DUSEL. Scenario C would enable the high-sensitivity neutrino experiment to operate during the decade, providing great sensitivity to matter-antimatter asymmetry in neutrinos. Scenario C would also enable new rare *K*-decay experiments highly sensitive to new physics.

At the Cosmic Frontier, Scenario C would advance the exploration of dark energy by enabling the timely completion of the two most sensitive detectors of dark energy, the JDEM space mission and the ground-based LSST telescope. Scenario C enables strategic, large-scale investments in exciting projects at the boundary between particle physics and astrophysics, the study of high-energy particles from space. Without these investments, the US will likely lose leadership in this rapidly developing area.

Budget scenario C would provide needed additional funds to advance accelerator R&D and technology goals. These goals go well beyond preparation for possible participation in ILC. Accelerator goals for the field include advancing the development of key enabling technologies such as superconducting rf technology, high-field magnet technology, high-gradient warm rf accelerating structures, rf power sources, and advanced accelerator R&D, all of which could greatly benefit from increased funding.

Increased funding in Scenario C would allow a robust detector R&D program in the U.S. to prepare for future experiments at both the energy and intensity frontiers.

Budget Scenario C provides desperately needed resources to rebuild university and laboratory infrastructure that has eroded during lean funding years and would allow retention and hiring of needed laboratory and university technical staff. This budget scenario would provide additional support for university groups, further addressing the pressing needs enunciated in several recent reports, among them the National Academy's "Rising Above the Gathering Storm."

Scenario D: Additional funding

The following scientific opportunities would justify additional funding above the level of the funding scenarios discussed above.

A lepton collider will be essential for the in-depth understanding of new physics discovered at the LHC: the source of the masses of the elementary particles, new laws of nature, additional dimensions of space, the creation of dark matter in the laboratory, or something not yet imagined. Major participation by the US in constructing such a facility would require additional funding beyond that available in the previous funding scenarios.

The study of dark energy is central to the field of particle physics. DOE is currently engaged with NASA in negotiations concerning the space-based Joint Dark Energy Mission. If the scale of JDEM requires significantly more funding than is currently being discussed, an increase in the budget beyond the previous funding scenarios would be justified.

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?

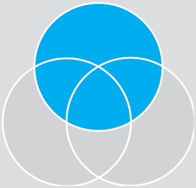
6. Why is the universe as we know it made of matter, with no antimatter present? What is the origin of this matter-antimatter asymmetry?

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.



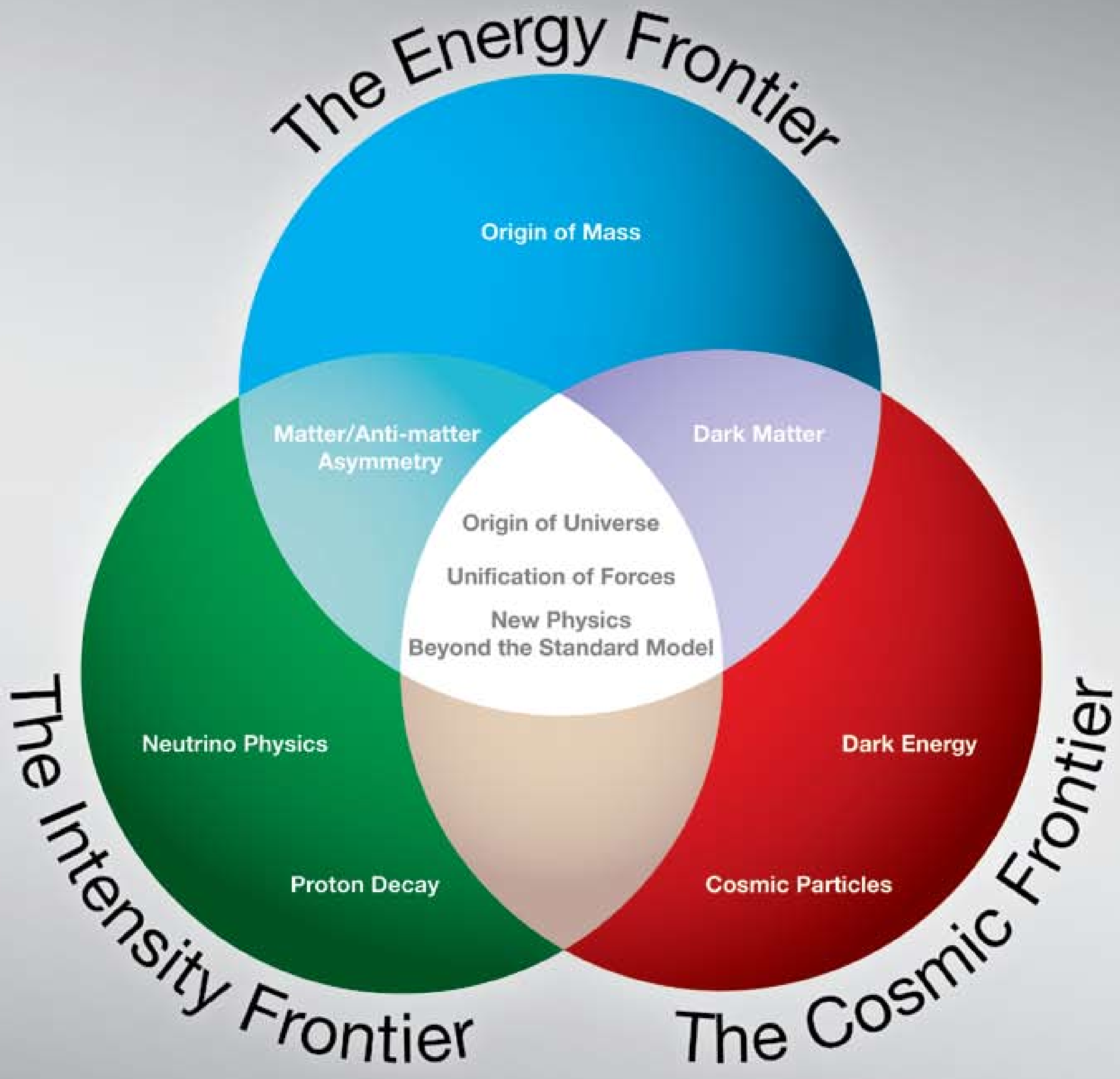
The Energy Frontier
Experiments at energy-frontier accelerators will make major discoveries leading to an ultimate understanding of particles and their interactions. Outstanding questions that present and future colliders will address include the origin of elementary particle masses, the possible existence 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.



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

Appendix 3

Economic and Societal Benefits

Although the purpose of particle physics research is to gain knowledge about the world around us and is not directly focused on applications, much of the research requires the development of new techniques. Particle physics is also not directly focused on education, but it has great impact as it inspires the young to technical and scientific careers and trains students rigorously who work in the field. The field thus contributes broadly through applications and education to the economic benefit of the society.

The attraction of Fermilab to young students is remarkable. Either directly or indirectly through their teachers we have connections to more than 30,000 students and 2000 teachers yearly in grades K through 12th. For many years we have hosted Saturday Morning Physics bringing students from the local high schools to Fermilab. Science fairs at the laboratory bring thousands of guests of all ages. Cosmic ray chambers at high schools allow students and their teachers to build a network to study extensive cosmic ray showers in the atmosphere.

Those students attracted to scientific careers will pursue advanced degrees in many of our research universities, all of which have strong particle physics groups that collaborate here and in Europe on forefront experiments. Fermilab has produced more than 1700 PhDs with nearly half coming from abroad. These students are trained technically and trained to work cooperatively with colleagues across the world. It is not unusual in particle physics collaborations to have colleagues from countries that are in conflict and at each other's throats working together to solve research problems at work or when breaking bread together.

Innovation has characterized particle physics. As technologies have found broad application, particle physicists cannot claim all the credit since as technologies evolve they advance in broad multidisciplinary fronts with many contributors. It is possible however to trace the origin of technologies to the early applications that establish their foundations. On these foundations industry produces practical products and tools. A study of these applications was done in connection with the Particle Physics Prioritization Panel of the HEPAP advisory committee in 2008 and its conclusions are reproduced below.

2 PARTICLE PHYSICS IN THE NATIONAL AND INTERNATIONAL CONTEXT

2.1 LONG-TERM VALUE OF RESEARCH IN FUNDAMENTAL SCIENCES

The drive to understand the world around us is a basic part of our humanity. Research in fundamental science provides the ideas and discoveries that form the long-term foundation for science and technology as a whole, which in turn drive the global economy and our very way of life.

In 2005, a panel of nationally recognized experts from across the spectrum of science and society, chaired by Norman Augustine, retired chairman and chief executive officer Lockheed Martin Corporation, produced "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future." To quote from the report:

> *"The growth of economies throughout the world has been driven largely by the pursuit of scientific understanding, the application of engineering solutions, and the continual technological innovation. Today, much of everyday life in the United States and other industrialized nations, as evidenced in transportation, communication, agriculture, education, health, defense, and jobs, is the product of investments in research and in the education of scientists and engineers. One need only think about how different our daily lives would be without the technological innovations of the last century or so."*

The "Gathering Storm" report makes the following recommendation:

> *"Sustain and strengthen the nation's traditional commitment to long-term basic research that has the potential to be transformational to maintain the flow of new ideas that fuel the economy, provide security, and enhance the quality of life"*

The "Gathering Storm" report was influential in forging a bipartisan accord in Washington to strive toward global leadership in science for the US by doubling the funding for research in the physical sciences over the next decade, among other actions.

Particle physics is a central component of the physical sciences, focused on the fundamental nature of matter and energy, and of space and time. Discoveries in particle physics will change our basic understanding of nature. Particle physics has inspired generations of young people to get involved with science, benefiting all branches of the physical sciences and strengthening the scientific workforce.

To quote from another National Academies report, “Charting the Course for Elementary Particle Physics,” the work of a panel including leaders from both science and industry and chaired by economist Harold Shapiro:

> *“A strong role in particle physics is necessary if the United States is to sustain its leadership in science and technology over the long term.”*

That report continues:

> *“The committee affirms the intrinsic value of elementary particle physics as part of the broader scientific and technological enterprise and identifies it as a key priority within the physical sciences.”*

Besides its long-term scientific importance, particle physics generates technological innovations with profound benefits for the sciences and society as a whole.

2.2 BENEFITS TO SOCIETY

It’s a simple idea. Take the smallest possible particles. Give them the highest possible energy. Smash them together. Watch what happens. From this simple idea have come the science and technology of particle physics, a deep understanding of the physical universe and countless benefits to society.

Each generation of particle accelerators and detectors builds on the previous one, raising the potential for discovery and pushing the level of technology ever higher. In 1930, Ernest O. Lawrence, the father of particle accelerators, built the first cyclotron at Berkeley, California. He could hold it in his hand. Larger and more powerful accelerators soon followed. After a day’s work, Lawrence often operated the Berkeley cyclotrons through the night to produce medical isotopes for research and treatment. In 1938, Lawrence’s mother became the first cancer patient to be treated successfully with particles from cyclotrons. Now doctors use particle beams for the diagnosis and healing of millions of patients. From the earliest days of high energy physics in the 1930s to the latest 21st-century initiatives, the bold and innovative ideas and technologies of particle physics have entered the mainstream of society to transform the way we live.

Some applications of particle physics—the superconducting wire and cable at the heart of magnetic resonance imaging magnets, the World Wide Web—are so familiar they are almost clichés. But particle physics has myriad lesser-known impacts. Few outside the community of experts who study the behavior of fluids in motion have probably heard of the particle detector technology that revolutionized the study of fluid turbulence in fuel flow.

What is unique to particle physics is the scale of the science: the size and complexity not only of accelerators and detectors but also of scientific collaborations. For example, superconducting magnets existed before Fermilab’s Tevatron, but the scale of the accelerator made the production of such magnets an industrial process, which led to cost-effective technology for magnetic resonance imaging. The World Wide Web was invented to solve the problem of communicating in an international collaboration of many hundreds of physicists. The scale on which particle physicists work results in innovations that broadly benefit society.

Selected examples from medicine, homeland security, industry, computing, science, and workforce development illustrate a long and growing list of beneficial practical applications with origins in particle physics.

Medicine: cancer therapy

The technologies of particle physics have yielded dramatic advances in cancer treatment. Today, every major medical center in the nation uses accelerators producing X-rays, protons, neutrons or heavy ions for the diagnosis and treatment of disease. Particle accelerators play an integral role in the advance of cancer therapy. Medical linacs for cancer therapy were pioneered simultaneously at Stanford and in the UK in the 1950s using techniques that had been developed for high energy physics research. This R&D spawned a new industry and has saved millions of lives.

Today it is estimated that there are over 7,000 operating medical linacs around the world that have treated over 30,000,000 patients.

Fermilab physicists and engineers built the nation’s first proton accelerator for cancer therapy and shipped it to the Loma Linda University Medical Center, where it has treated some 7,000 patients. Relative to X-rays, proton therapy offers important therapeutic benefits, especially for pediatric patients. The Neutron Therapy Facility at Fermilab has the highest energy and the deepest penetration of any fast neutron beam in the United States. Neutrons are effective against large tumors. More than 3,500 patients have received treatment at the Neutron Therapy Facility.

Medicine: diagnostic instrumentation

Particle physics experiments use an array of experimental techniques for detecting particles; they find a wide range of practical applications. Particle detectors first developed for particle physics are now ubiquitous in medical imaging. Positron emission tomography, the technology of PET scans, came directly from detectors initially designed for particle physics experiments sensing individual photons of light. Silicon tracking detectors, composed of minute sensing elements sensitive to the passage of single particles, are now used in neuroscience experiments to investigate the workings of the retina for development of retinal prosthetics for artificial vision.

Homeland security: monitoring nuclear nonproliferation

In nuclear reactors, the amount of plutonium builds up as the uranium fuel is used, and the number and characteristics of antineutrinos emitted by plutonium differ significantly from those of antineutrinos emitted by uranium. This makes it possible for a specially doped liquid scintillator detector monitoring the antineutrino flux from a nuclear reactor core to analyze the content of the reactor and verify that no tampering has occurred with the reactor fuel. Lawrence Livermore National Laboratory has built and is testing a one-ton version of this type of detector, originally developed by high energy physicists to study the characteristics of neutrinos and antineutrinos, as a demonstration of a new monitoring technology for nuclear nonproliferation.

Industry: power transmission

Cables made of superconducting material can carry far more electricity than conventional cables with minimal power losses. Underground copper transmission lines or power cables are near their capacity in many densely populated areas, and superconducting cables offer an opportunity to meet continued need. Further superconducting technology advances in particle physics will help promote this nascent industry.

Industry: biomedicine and drug development

Biomedical scientists use particle physics technologies to decipher the structure of proteins, information that is key to understanding biological processes and healing disease. To determine a protein’s structure, researchers direct the beam of light from an accelerator called a synchrotron through a protein crystal. The crystal scatters the beam onto a detector. From the scattering pattern, computers calculate the position of every atom in the protein molecule and create a 3-D image of the molecule. A clearer understanding of protein structure allows for the development of more effective drugs. Abbott Labs’ research at Argonne National Laboratory’s Advanced Photon Source was critical in developing Kaletra®, one of the world’s most-prescribed drugs to fight AIDS. Next-generation light sources will offer still more precise studies of protein structure without the need for crystallization.

Industry: understanding turbulence

Turbulence is a challenge to all areas of fluid mechanics and engineering. Although it remains poorly understood and poorly modeled, it is a dominant factor determining the performance of virtually all fluid systems from long distance oil pipelines to fuel injection systems to models for global weather prediction. Improvements to our knowledge will have payoffs in reducing energy losses in fuel transport, improving efficiency of engines and deepening our understanding of global climate behavior. Technology developed for particle physics and applied to problems of turbulence has extended our understanding of this difficult phenomenon by more than tenfold. Silicon strip detectors and low-noise amplifiers developed for particle physics are used to detect light scattered from microscopic tracer particles in a turbulent fluid. This technique has permitted detailed studies of turbulence on microscopic scales and at Reynolds numbers more than an order of magnitude beyond any previous experimental reach.

Computing: the World Wide Web

CERN scientist Tim Berners-Lee developed the World Wide Web to give particle physicists a tool to communicate quickly and effectively with globally dispersed colleagues at universities and laboratories. The Stanford Linear Accelerator Center had the first Web site in the United States, Fermilab had the second. Today there are more than 150 million registered Web sites. Few other technological advances in history have more profoundly affected the global economy and societal interactions than the Web. Revenues from the World Wide Web exceeded one trillion dollars in 2001 with exponential growth continuing.

Computing: the Grid

Particle physics experiments generate unprecedented amounts of data that require new and advanced computing technology to analyze. To quickly process this data, more than two decades ago particle physicists pioneered the construction of low-cost computing farms, a group of servers housed in one location. Today, particle physics experiments push the capability of the Grid, the newest computing tool that allows physicists to manage and process their enormous amounts of data across the globe by combining the strength of hundreds of thousands of individual computers. Industries such as medicine and finance are examples of other fields that also generate large amounts of data and benefit from advanced computing technology.

Sciences: synchrotron light sources

Particle physicists originally built electron accelerators to explore the fundamental nature of matter. At first, they looked on the phenomenon of synchrotron radiation as a troublesome problem that sapped electrons’ acceleration energy. However, they soon saw the potential to use this nuisance energy loss as a new and uniquely powerful tool to study biological molecules and other materials. In the 1970s, the Stanford Linear Accelerator Center built the first large-scale light source user facility. Now, at facilities around the world, researchers use the ultra-powerful X-ray beams of dedicated synchrotron light sources to create the brightest lights on earth. These luminous sources provide tools for protein structure analysis, pharmaceutical research and drug development, real-time visualization of chemical reactions and biochemical processes, materials science, semiconductor circuit lithography, and historical research and the restoration of works of art.

Sciences: spallation neutron sources

Using accelerator technologies, spallation neutron sources produce powerful neutron beams by bombarding a mercury target with energetic protons from a large accelerator complex. The protons excite the mercury nuclei in a reaction process called spallation, releasing neutrons that are formed into beams and guided to neutron instruments. Using these sophisticated sources, scientists and engineers explore the most intimate structural details of a vast array of novel materials.

Sciences: analytic tools

Particle physicists have developed theoretical and experimental analytic tools and techniques that find applications in other scientific fields and in commerce. Renormalization group theory first developed to rigorously describe particle interactions has found applications in solid state physics and superconductivity. Nuclear physics uses chiral lagrangians, and string theory has contributed to the mathematics of topology. Experimental particle physicists have also made contributions through the development of tools for extracting weak signals from enormous backgrounds and for handling very large data sets. Scientists trained in particle physics have used neural networks in neuroscience to investigate the workings of the retina and in meteorology to measure raindrop sizes with optical sensors.

Workforce development: training scientists

Particle physics has a profound influence on the workforce. Basic science is a magnet that attracts inquisitive and capable students. In particle physics, roughly one sixth of those completing Ph.D.s ultimately pursue careers in basic high-energy physics research. The rest find their way to diverse sectors of the national economy such as industry, national defense, information technology, medical instrumentation, electronics, communications, biophysics and finance—wherever the workforce requires highly developed analytical and technical skills, the ability to work in large teams on complex projects, and the ability to think creatively to solve unique problems.

A growing list

The science and technology of particle physics have transformational applications for many other areas of benefit to the nation's well-being.

- Food sterilization
- Medical isotope production
- Simulation of cancer treatments
- Reliability testing of nuclear weapons
- Scanning of shipping containers
- Proposed combination of PET and MRI imaging
- Improved sound quality in archival recordings
- Parallel computing
- Ion implantation for strengthening materials
- Curing of epoxies and plastics
- Data mining and simulation
- Nuclear waste transmutation
- Remote operation of complex facilities
- International relations

At this time there exist few quantitative analyses of the economic benefits of particle physics applications. A systematic professional study would have value for assessing and predicting the impact of particle physics technology applications on the nation's economy.

2.3 THE INTERNATIONAL CONTEXT

The scientific opportunities provided by particle physics bring together hundreds of scientists from every corner of the globe to work together on experiments and projects all over the world. Both the technical scale and the costs of today's large accelerators put them beyond the reach of any single nation's ability to build or operate. Particle physics projects now take shape as international endeavors from their inception. These scientific collaborations take on new significance as beacons for free and open exchange among men and women of science of all nations. They offer an inspiring model for cooperation from a field long known for its leadership in international collaboration.

Collider experiments have had strong international collaboration from the outset. Experiments at CERN, Fermilab and SLAC combined the strengths of US, European and Asian groups to achieve the groundbreaking discoveries that define particle physics today. Accelerator design and construction is now a joint effort as well. American accelerator physicists and engineers helped the Europeans build the Large Hadron Collider at CERN and collaborated with the Chinese to build the Beijing Electron-Positron Collider. The GLAST project involves a seven-nation collaboration of France, Germany, Italy, Japan, Spain, Sweden and the US.

Japan is currently constructing a 50-GeV proton synchrotron at the Japan Proton Accelerator Research Complex. The JPARC synchrotron will produce an intense neutrino beam aimed at the large Super-Kamiokande detector to study neutrino oscillations and matter-antimatter asymmetry. This experiment has significant US participation, as did its predecessors. US physicists are also working on two overseas reactor neutrino experiments, Daya Bay in China and Double Chooz in France.

The KEK *B*-Factory and the Belle detector continue to operate, and plans are under way to significantly increase the collider's beam intensity to improve sensitivity to physics beyond the Standard Model. Modest US participation continues in this collaboration. At lower energies, the new BEPC-II collider in China is about to start operation. A number of US groups are working on its experimental program.

Cosmic Frontier experiments have also involved international collaboration, but on a smaller scale due to the hitherto modest size of the experiments. Here too, however, the magnitude of future experiments makes international collaboration essential.

Planning for the future of the field is also international. Both HEPAP and P5 have members from Europe and Asia, essential for understanding the current and future programs in those regions at all three scientific frontiers in particle physics.

The transformation occurring in the international scene has presented challenges to this panel. Free access for physicists of all nations to the world's accelerators rests on the assumption that each region takes its share of responsibility by building and operating such facilities. In recent decades, each region hosted major collider experiments and a variety of smaller experiments. But now, with the end of both the Cornell and SLAC collider programs and with the Fermilab Tevatron collider about to complete its program in the next few years, the map of the field is changing rapidly. Most of the accelerator-based experiments in the near term will occur overseas. The panel has given careful consideration to how the changing international context will affect the ability of the US to pursue most effectively the extraordinary scientific opportunities that lie ahead and to remain a world leader in the field of particle physics.

Appendix 4

Short Biography of Piermaria Oddone

Oddone was appointed Director of Fermi National Accelerator Laboratory in July, 2005. Fermilab, a US Department of Energy Laboratory, is managed by Fermi Research Alliance (FRA), a partnership of the University of Chicago and the Universities Research Association (URA). Fermilab advances the understanding of matter, energy, space and time through the study of elementary particle physics. Fermilab provides cutting edge particle accelerators and detectors to qualified researchers to conduct basic research at the frontiers of particle physics and related disciplines. Fermilab also has a vital program in particle astrophysics and cosmology linking the physics of elementary particles to the evolution and fate of the Universe.

Oddone was previously Deputy Director of the Lawrence Berkeley National Laboratory, with primary responsibility for the scientific development of the laboratory and its representation to the agencies. Achievements during his tenure as Deputy Director include gaining the National Energy Super Computer Center (NERSC), launching and developing the Joint Genome Institute (JGI), breaking ground on the Molecular Foundry (the LBNL nanosciences center), establishing major new programs in quantitative biology, astrophysics and computer science and exploiting the Advanced Light Source (ALS).

Oddone's research has been in experimental particle physics and based primarily on electron-positron colliders at the Stanford Linear Accelerator Center (SLAC). He invented the Asymmetric B-Factory, a new kind of elementary particle collider to study the differences between matter and antimatter and worked in the development of the PEP II Asymmetric B-Factory at SLAC (a second one was built in Tsukuba, Japan) and the formation of the large international collaboration, *BaBar*, to exploit its physics opportunities. Together with the *Belle* detector in Japan, *BaBar* discovered the violation of matter-antimatter symmetry in the decay of particles containing the *b* quark. Hundreds of researchers have exploited the B-Factories over the last decade, developing a precise understanding of the quark model. Oddone received the 2005 Panofsky Award of the American Physical Society for the invention of the Asymmetric B-Factory. He is a Fellow of the American Physical Society. He was elected as Fellow of the American Academy of Arts & Sciences in 2008. He also is a member of the Executive Council of the National Laboratory Directors Council (NLDC).

Oddone was born in Arequipa, Peru, and is a U.S. citizen. After receiving his undergraduate degree from MIT, Oddone received his PhD in Physics from Princeton University followed by a post-doctoral fellowship at Caltech. He joined the Lawrence Berkeley National Laboratory in 1972.