Executive Summary

The 2013 Community Summer Study (known as "Snowmass") brought together nearly 700 physicists to identify the critical research directions for the United States particle physics program. Commissioned by the American Physical Society, this meeting was the culmination of intense work over the past year that defined the most important questions for this field and identified the most promising opportunities to address them. The full written report of the Summer Study is intended to be a key resource for setting priorities in particle physics.

To understand the universe, particle physics addresses two main questions: What are the most elementary constituents of nature and what are the forces that cause them to interact? These questions are deeply fundamental and the desire to explore them is a defining characteristic of the human spirit. At the same time, finding the answers has practical value because it drives technical innovation in instrumentation, computing, and accelerators. This development of new technology has continually improved the quality of human life, from industrial techniques, to medical imaging, to computing, and beyond.

The discovery of the Higgs boson in 2012 completes the picture of the particle world called the Standard Model, a remarkable achievement made possible by decades of worldwide collaboration. However, the Standard Model still leaves significant questions unanswered: What is the nature of the Higgs boson? What do neutrino masses tell us? Are the known forces part of a unified structure? What is the composition of 95% of the universe? What mechanism explains the dominance of matter over antimatter? To answer these questions, a variety of techniques are needed. Particle physics uses three basic approaches, often characterized as exploration across the cosmic, energy, and intensity frontiers. Each employs its own tools and techniques, but they ultimately address the same fundamental questions.

These approaches require long-term vision and global partnerships. In designing a program, the priorities of other regions of the world must be taken into account. The U.S. brings crucial design talent, technology, knowledge and resources that benefit progress in this field regardless of where each experiment is located.

The outline that follows introduces the future directions necessary for further progress in our understanding of nature. ~~We use the language of "Frontiers" as describing the different experimental approaches as well as the enabling technologies required~~. Their order does not reflect prioritization.

Particle Physics Frontiers

Intensity Frontier. Experiments at the "Intensity Frontier" explore fundamental questions by using precision measurements to probe quantum effects. They encompass searches for extremely rare processes and for tiny deviations from Standard Model expectations. They have the potential to expose shortcomings in our current understanding and to discover new laws of physics at very high energies, in many cases exploring beyond the direct reach of high-energy accelerators. This program requires the greatest possible beam intensities, as well as ultra-sensitive, sometimes massive detectors. Facilities and experiments that will position the U.S. as a global leader in intensity frontier science were studied at the Snowmass meeting.

Neutrinos are the most elusive of the known fundamental particles. Snowmass underscored the reality that we are entering the era of precision neutrino physics in which we can test the three-neutrino paradigm to high accuracy. In light of the recent discovery that the value of θ_{13} is large, there is a clear experimental path forward to determine the properties of neutrinos. The Long-Baseline Neutrino Experiment (LBNE) will measure the mass hierarchy and is uniquely positioned to determine whether CP symmetry is violated in the leptonic sector. Future multi-megawatt beams aimed at LBNE, such as those provided from Project X, would enable measurement of the CP-violating phase with conclusive accuracy. An underground LBNE detector also allows for the study of atmospheric neutrinos, nucleon decay, and precision measurements from a galactic supernova explosion. This represents a vibrant global program with the U.S. as host.

Further opportunities to study neutrinos were articulated at Snowmass. An upgrade of the IceCube experiment would provide a promising approach to measure the mass hierarchy using atmospheric neutrinos. Next-generation neutrinoless double-beta decay experiments can reach the sensitivity necessary to determine whether neutrinos are their own antiparticles and are a critical component of a strong neutrino program.

Flavor observables provide essential probes of new physics. Substantial progress is anticipated this decade with experiments utilizing the Main Injector at Fermilab. These include new measurements of the anomalous magnetic moment of the muon and a sensitive search for muon-electron conversion. The proposed experiment ORKA would probe rare kaon decays to a new level of precision and would retain the U.S. capability to perform quark-flavor experiments. Project X could provide the means to probe electric dipole moments at the levels predicted in many models of CP violation. Snowmass studies showed that the U.S. can capitalize on current investments and that unprecedented sensitivities can be acheived with the capabilities offered by LHCb at CERN, Belle-II in Japan, BESIII in China, and the experiments served by the intense proton source from Project X at Fermilab. Each of these experiments probes a different aspect of new physics in its unique way.

Dark sectors containing new light weakly coupled particles appear in well-motivated theories. Searches for these particles may proceed with existing facilities, utilizing intense beams and comparatively modest experiments. Studies at Snowmass identified a rich, diverse, and low-cost program that has the potential for high-impact discoveries, thus illustrating the importance of experiments at a variety of scales.

Energy Frontier. The mysteries of the newly discovered Higgs boson were a major theme at Snowmass. The properties of the Higgs boson raise crucial questions that guide large parts of the future particle physics program. Indeed, this discovery changes everything. It calls for a three-pronged research program at high-energy accelerators:

first, to determine the properties of the Higgs boson as accurately as possible; second, to make precise measurements of the heavy particles W, Z, and the top quark, which can carry the imprint of the Higgs field; and, third, to search for new particles predicted by models of the Higgs boson and electroweak symmetry breaking. These questions also overlap with those in other frontiers. The expectation of TeV-scale particles directly motivates the search for WIMP Dark Matter and flavor-changing rare decays.

For at least the next fifteen years, the experiments at the Large Hadron Collider at CERN will drive the Energy Frontier program forward. The Higgs boson discovery at the LHC now becomes a precision study of the properties of this particle. The high-luminosity LHC will measure Higgs boson couplings at the few-percent level and provide the first measurement of the Higgs self-coupling. The steps of the LHC to 300 fb^{-1} and then to 3000 fb^{-1} will explore deeply for new particles produced through either the strong or the electroweak interactions. They will probe for new dynamics of W, Z, and Higgs at TeV energies and study rare decays using a sample of billions of top quarks. The LHC experiments have already proven their ability to work as global collaborations. U.S. contributions to the leadership, detector and accelerator components, technology, and physics insight have been indispensable.

There is compelling scientific motivation for continuing this program with lepton colliders. Experiments at these accelerators can reach sub-percent precision in Higgs boson properties in a unique, model-independent way, enabling discovery of percent-level deviations predicted in theoretical models. They can improve the precision of our knowledge of the W, Z, and top properties by an order of magnitude, allowing the discovery of predicted new physics effects. They search for new particles with unequivocal discovery or exclusion, complementing new particle searches at the LHC. A global effort has now completed the technical design of the International Linear Collider (ILC) accelerator and detectors that will provide these capabilities. The Japanese particle physics community has named this facility as its first priority.

The Snowmass study considered many other options for high-energy colliders that might be realized over a longer term. These included higher energy linear colliders, circular e+e- colliders, muon colliders, and photon colliders and all merit continued study. The Snowmass study identified in particular the promise of a 100 TeV-class hadron collider, giving a large step in energy with great potential for new insights into electroweak symmetry breaking, naturalness, and dark matter. This opportunity should be clarified through renewed accelerator R&D and physics studies for such a machine over the next decade.

In all of the projects listed above, U.S. leadership in developing detector and accelerator technologies is playing a critical role. These U.S. initiatives are essential to meet the world-wide scientific goals in particle physics.

Cosmic Frontier. As successful as it has been, the Standard Model describes only 5% of the universe. The remaining 95% is in the form of dark matter and dark energy, whose fundamental nature is almost completely unknown. Experiments at the "Cosmic

Frontier" include innovative, interdisciplinary approaches to determine the nature of dark matter and dark energy and to use the universe as a laboratory to search for new fundamental particles and interactions.

The Snowmass process produced a clear articulation of how the different approaches to dark matter – direct detection, indirect detection, accelerator-based searches, simulations, and astrophysical surveys – each provide unique and necessary information. The process also produced a census of present-day and proposed experiments and their capabilities. The new direct and indirect detection experiments will provide leaps in sensitivity at relatively modest cost, probe dark matter masses inaccessible to colliders, and bring us to a realm in which major discoveries could be imminent.

Snowmass also strongly reinforced the roles that cosmic surveys play in particle physics. Stage III and Stage IV dark energy imaging and spectroscopic surveys will shrink the errors as recommended in previous community studies, but they will do even more for particle physics: the richness of the data and detailed attention to systematic error management will enable many new tests of the behavior of dark energy and general relativity over a wide range of distance scales and settings. Cosmic microwave background (CMB) experiments will probe the physics of inflation, with sufficient sensitivity to falsify significant classes of models.

Remarkably, future cosmic surveys, as well as future polar-ice neutrino projects, will also provide precise information about neutrino properties, including the mass hierarchy, the number of light neutrinos, and the sum of the masses of the neutrino species. Combining this information with accelerator-based and reactor-based neutrino experiments, as well as other experiments such as those searching for neutrinoless double-beta decay, will accelerate our understanding of fundamental neutrino properties and enable us to derive meaning from potential inconsistencies.

Finally, the Snowmass process reiterated the unique information we can gain from studies of cosmic particles and the detection of significant numbers of the highest energy cosmic rays produced in nature. These studies include the detection of GZK neutrinos, an extremely high-energy flux of neutrinos produced in the interactions of cosmic rays with CMB photons, which will enable the study of neutrino interactions at center-of-mass energies up to 100 TeV, well beyond the reach of colliders.

Essential technologies and facilities, and required advances in theory, were identified for all these areas.

In summary, together with the other frontier areas, the "Cosmic Frontier" provides to particle physics clear evidence for physics beyond the Standard Model; profound questions of popular interest; frequent new results and surprises with broad impacts; large discovery space with unique probes; important cross-frontier topics; and a full range of project scales, providing flexible programmatic options. The largest projects are, appropriately and necessarily, international. The U.S. is still the leader in this quickly evolving area, but other regions with intensive interest in this physics are advancing rapidly.

Theoretical Physics: Progress in particle physics requires interplay between theory and experiment. The U.S. has been the world leader for many decades in particle theory, and a sustained strong and vibrant program remains essential for the success of U.S. particle physics. Theory has been a driving force in both the development and testing of the Standard Model, including the discovery of the Higgs boson. Theory has been critical in formulating the big questions in the field, setting out hypotheses that address them, and proposing experimental strategies to confirm or refute them. At the same time, theorists seek new structures that might provide unanticipated results. The success of the U.S. program has rested on principal investigators in universities and national labs, working with postdoctoral fellows and graduate students, and collaborating with both U.S. and international researchers.

Enabling Frontiers

Capabilities Frontier. Delivering frontier physics opportunities relies on the continuing development of the physics and technology of particle accelerators. The U.S. has historically been a leader in that development.

The LHC incorporates major U.S. contributions. For the future, the U.S. laboratories have pioneered the technology of Nb_3Sn magnets that permit higher fields than possible with the present LHC technology. Through the US-LHC Accelerator Research Program (LARP), the U.S. has a world-leading capability to develop high-field superconducting accelerator magnets – a central capability for the LHC luminosity upgrade and for a future proton collider of far greater energy than the LHC. A 100 TeV-class hadron collider (VLHC) is within the development reach of existing materials for a tunnel of 100 km or larger. Higher energy may require new classes of superconducting magnets and novel ways of handling synchrotron radiation.

As described in its Technical Design Report, the ILC is ready to proceed to construction. Its design incorporates U.S. contributions in accelerator theory, damping ring design, superconducting RF technology, and beam control and delivery. Longer range concepts for multi-TeV lepton colliders include the CLIC two-beam accelerator, plasma wakefield accelerators, and – if proven feasible – a muon collider.

Accelerators for proposed intensity frontier experiments have the common requirements of delivering multi-Mega-Watt proton beams with flexible, experiment-dependent timing structure - demands that are beyond the capabilities of any existing accelerator. The proposed Project X would deliver beams over the energy range 0.25 to 120 GeV. High current DAEδALUS cyclotrons for neutrino studies would complement this program.

Managing stored energy and controlling beam loss are critical to all accelerators. Technical challenges include generating high quality beams, modeling beam dynamics, and managing material damage in high power targets.

Maximizing the potential of future accelerators requires advancing critical technologies without sacrificing visionary, innovative research in basic accelerator science. The many applications of superconducting technology to all accelerator-based science exemplify the payoff of long-range investment beyond the confines of individual projects. Integrated multi-laboratory programs to mature technology to engineering readiness are essential to the success of future projects. Investment in the U.S. system of national laboratories and research universities, with their broad expertise and technical infrastructure, will yield new generations of accelerators capable of higher energies, more luminous beams, and more efficient operation. A strong program of R&D and accelerator stewardship will benefit all areas of science and industry that use accelerator technology.

Many experiments searching for dark matter, proton decay, or seeking to determine the properties of neutrinos must be located underground to shield the sensitive experiments from cosmic ray backgrounds. Underground facilities are located or proposed in North and South America, Europe, Asia and in the Antarctic ice. The scope of underground capabilities in all regions is expected to increase by the end of the decade to accommodate the experimental demand. Locating LBNE underground in South Dakota would allow this experiment to realize its full scientific potential and could make it an anchor for possible future domestic underground capabilities for a broader range of compelling experiments.

Instrumentation Frontier. Instrumentation enables experiments to answer the science questions described above. Particle physics has a long and distinguished history of inventing, designing, and building the specialized instrumentation required for its experimental research. At Snowmass, a vision for a U.S. instrumentation program for particle physics was formulated which would enable the U.S. to maintain a scientific leadership position in a broad, global, experimental program. The program's strategy is to identify and develop technologies that will overcome key barriers to answering the science questions. Important technology areas for further investment were identified at Snowmass.

Executing this strategy requires integrating the diverse capabilities and resources of universities, national laboratories, other branches of science, and industry into detector R&D collaborations, emphasizing the importance of innovation through a domestic instrumentation development program. A coordinating panel would help articulate the mission of this program and facilitate activities in order to translate its implementation. The goals of the program are to develop both incremental and transformational, cost-effective technologies with maximal scientific reach, based on the technological strengths in the US. A stable and adequately funded generic instrumentation program will ensure that particle physics invests in its future and establishes a foundation for a competitive, healthy program in the long term.

Computing Frontier. Computing is a major component of all particle physics experiments and in many areas of theoretical physics. The “Computing Frontier” was divided into a number of subgroups covering user needs and infrastructure. The user needs groups covered each of the experimental frontiers and four theoretical areas. The infrastructure groups examined trends in computing to predict how technology will evolve and how it will affect the costs and capabilities of computing systems, networks, and storage.

A number of concerns were identified. Given the changes in chip technology and evolution of performance systems to include multi-core chips and accelerators, how will we write the parallel codes that will be needed in the future and how will we train the personnel to develop, support and maintain them? Upgrades to the LHC will place more demands on the distributed computing systems for ATLAS and CMS. Attention needs to be paid to wide-area networking trends to ensure that the network does not become a bottleneck in the future. It would be desirable to better coordinate software development for a number of intensity frontier experiments whose needs will become substantial. The price of storage and bandwidth of disks may be of significant concern in the future. Prices may not drop as rapidly as in the past and, while disks have become larger, their interfaces have not become significantly faster. Early attention to these issues has the potential to increase efficiency, reduce costs, enable significantly more realistic theoretical calculations, and avoid computing bottlenecks in the experimental program that could limit scientific progress.

Communication, Education and Outreach

The particle physics community recognizes the critical importance of consistent and coherent communication, education and outreach. These foster nationwide support for the field, develop the next generation of physicists and ensure scientifically literate citizens. More physicists must engage in CEO activities to translate the American public's fascination for particle physics research into the support necessary to enable the field to answer its biggest questions. Existing activities must be augmented with dedicated personnel who will enhance these efforts, provide nationwide coordination, and spearhead new initiatives. Such actions include a central communication, education and outreach office for physicists, materials designed to inform the public about direct and indirect applications of particle physics research, sustainable methods to collect statistics on workforce development and technology transfer, professional development opportunities for educators, and new learning opportunities for students of all ages.

Particle physicists are pioneers of large scientific projects. The Tevatron and now the Large Hadron Collider give examples of projects that were developed over 25 years, with global collaboration, that led to crowning discoveries. As these projects were developed, we have evolved a scientific community that links together scientists from all over the world pursuing common goals. With the directions described above, we will achieve more successes in the future in our common quest to gain a fuller understanding of the universe.