Executive Summary

The 2013 Community Summer Study (known as "Snowmass") brought together nearly 700 physicists to identify the critical research directions for the U.S. particle physics program. This meeting was the culmination of intense work over the last 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 HEPAP, DOE and NSF in 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?. While these questions are esoteric, finding answers requires significant technical leaps 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 approaches is needed rather than a single experiment or technique. Particle physics uses three basic approaches, often characterized as exploration across the cosmic, energy, and intensity frontiers. Each approach employs different 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 need to 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 for the enabling technologies required to execute the program. 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 failings 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. The Snowmass studies proposed facilities and experiments that will position the US as a global leader in intensity frontier science.

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 the CP symmetry is violated in the leptonic sector. Future multi-megawatt beams aimed at LBNE, such as those provided from Project X, will be necessary to measure the CP violating phase with sufficient accuracy. An underground LBNE laboratory also allows for the study of atmospheric neutrinos, nucleon decay, and precision measurements of neutrinos from a galactic supernova explosion. This represents a vibrant global program with the US as host.

Further opportunities to study neutrinos were articulated at Snowmass. An upgrade of the IceCube experiment, provides a promising approach to measure the mass hierarchy using atmospheric neutrinos. Next-generation neutrinoless double-beta decay experiments can reach the sensitivity 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 deep search for muon-electron conversion. Proposed experiments would probe rare kaon decays to a new level of precision and would retain the US capability to perform heavy quark experiments. Project X will provide the means to probe electric dipole moments at the levels predicted in models of CP violation. Snowmass studies showed that the US can capitalize on current investments and achieve unprecedented sensitivities with the capabilities offered by LHCb at CERN, Belle-II in Japan, and the intense proton source from Project X at Fermilab. Each of these flavor 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.

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. These questions call for a three-pronged research program at high energy accelerators: first, to search for new particles with TeV masses predicted by models of electroweak symmetry breaking; second, to make precise measurements of the heavy particles W, Z, and the top quark, which can carry the imprint of the Higgs; and, third, to measure the properties of the Higgs boson itself to very high precision. Questions about the Higgs boson also inspire the search for the dark matter particles and for flavor-changing rare decays, since in both cases, the motivating theory often comes from models of the Higgs and its role in symmetry-breaking.

For at least the next fifteen years, the experiments at the Large Hadron Collider at CERN will drive the energy frontier program forward. Especially in its high-luminosity phase the LHC is expected to explore deeply for new particles produced through either the strong or the electroweak interactions. The LHC will study rare decays using a sample of billions of top quarks and probe for new dynamics of W, Z, and Higgs at TeV energies. It will measure Higgs boson couplings at the few-percent level and provide the first measurement of the Higgs self-coupling. The LHC experiments have already proven their ability to work as global collaborations. Technology, insights, and leadership from the US have played indispensible roles in these experiments.

There is strong scientific motivation for continuing this program with lepton colliders. Experiments at lepton colliders allow searches for new particles with unequivocal discovery or exclusion, complementing those at the LHC. They can improve the precision of our knowledge of the W, Z, and top properties by an order of magnitude, potentially bringing these measurements into confrontation with theory. They can reach sub-percent precision in the Higgs boson properties, allowing discoveries of percent-level deviations predicted in theoretical models. A global effort has now completed the technical design of the International Linear Collider (ILC), an accelerator that will provide these capabilities. The Japanese high energy 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 linear and circular e+e- colliders, muon colliders, and photon colliders. Serious study was begun on the physics program of future proton colliders at 33 and 100 TeV center of mass energy.

Cosmic Frontier. Experiments at the “Cosmic Frontier” include innovative, interdisciplinary approaches to solving the mysteries of dark matter and dark energy, which are the dominant components of the universe but whose fundamental nature is almost completely unknown.

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, as well as a census of present-day and proposed facilities and their capabilities. The leaps in sensitivity of the new facilities 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, including detection of GZK neutrinos, an extremely high-energy flux of neutrinos that will enable the study of interactions at energies of 100 TeV, and detection of significant numbers of the highest energy cosmic rays produced in nature. Essential technologies and facilities, and required advances in theory, were identified for all these areas

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 US has been the world leader for many decades in particle theory, and a sustained strong and vibrant program remains essential for the success of US particle physics. Theory has been a driving force both in the development and testing of the Standard Model, including the Higgs discovery. 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 resolutions. The success of the US program has rested on principal investigators in universities and national labs, working with postdoctoral fellows and graduate students, and collaborating with both US and international researchers.

Enabling Frontiers

Capabilities Frontier. Accelerators for the widely diverse range of next generation intensity frontier experiments have the common requirements of delivering muti-MW proton beams with a flexible, experiment-dependent timing structure. Such requirements are beyond the capabilities of any present accelerator. The proposed Project X, when fully realized, would deliver such beams over a broad energy range from 0.25 to 120 GeV. It would also be a platform for future muon facilities with muon storage rings as a possible first step toward neutrino factories. Innovative cyclotrons for neutrino studies may be part of this program. Critical technical issues that must be addressed for all proposed intensity frontier accelerators include controlling beam loss and understanding the limits of material damage in high power targets.

The currently proposed energy frontier accelerators incorporate significant US contributions to the accelerator technology, both for the LHC and for the ILC. US physicists are involved in the upgrades of the LHC accelerator through the LHC Accelerator Research Program (LARP). The technology of Nb_3Sn superconducting magnets, pioneered in the US and developed for application through LARP, has a key role in the high-luminosity proposal. The ILC design embodies US leadership contributions in beam dynamics, superconducting RF technology, damping ring design, and beam delivery. This design is ready to proceed to construction.

Innovative concepts for higher energy accelerators, both proton-proton and lepton colliders, to be realized on much longer time scales, were also discussed. The CLIC two-beam accelerator is based on X-band, warm linac technology, with a 50 km length to reach 3 TeV. A second approach is to cool and collide muon beams. This muon collider – if proven feasible – would fit a 3 TeV collider onto the present Fermilab site. The muon beam approach has a very large overlap with capabilities needed for intensity frontier accelerators. A third approach would use wakefields driven either by beams or lasers to achieve accelerating fields of 10 to 100 GeV per meter. A hadron collider of higher energy can be designed within the development reach of existing materials and technologies for a tunnel of 100 km or larger. Higher energy or lower cost would require development of new classes of superconducting magnets. US scientists are currently leading the development of high field magnets, the key enabling technology in the quest for higher energies.

Maximizing the potential of any next energy frontier accelerator will require continuing an integrated multi-laboratory engineering program carrying out innovative long-range research. The US national laboratories, with their unique expertise, should invest in the development of technologies for accelerators capable of higher energies, more luminous beams, and more efficient operation that will provide the setting for future high energy physics experiments This program of R&D and accelerator stewardship is likely to bring benefits to all areas of science and industry that make use of 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 Antarctica ice. About 1,000 particle physicists from the United States (and more from outside the United States) are currently taking part in experiments in underground facilities around the world. The scope of underground capabilities in all regions is expected to increase by the end of the decade to accommodate increased experimental demand. Locating the Long Baseline Neutrino Experiment (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. The "Instrumentation Frontier" enables experiments to answer the science questions described above. High Energy Physics has a long and distinguished history of inventing, designing and building the specialized instrumentation required for its experimental research. At Snowmass, the vision for a US instrumentation program for particle physics was formulated, which would enable the US to maintain a scientific leadership position in a broad, global, experimental program. The program's strategy is to identify from the plethora of technologies those that will overcome key barriers to answering the science questions. Some key technology areas for further investment have been 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, which would reestablish the importance of innovation through a domestic instrumentation development program. A coordinating panel will help articulate the mission of this program and facilitate 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 stably 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 high 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 are not at the level of LHC experiments, but will nevertheless 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 CE\&O 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.

High-energy 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 program outlined above, we will achieve more successes in the future in our common quest to gain a fuller understanding of the universe.

Big Questions for Particle Physics

Through the previous six decades of precision and discovery-level particle physics, we have learned much about the basic laws that govern the universe. We have uncovered the laws that describe the subnuclear forces and, with the discovery of the Higgs boson, the agent that we believe should give mass to all elementary particles. However, there is still much that we do not understand. The advance in our knowledge of elementary particle physics has sharpened the questions in that domain. Recent discoveries about the matter and energy content of the universe have brought new questions that are equally fundamental, and equally vexing.

One of the goals of Snowmass was to develop a framework of scientific questions that can form the basis for a future program in particle physics. To introduce a summary of the results of Snowmass, we propose a set of ten Particle Physics Questions. The search for their answers will be carried out with a broad range of experimental methods, cutting across the "frontiers" around which the Snowmass study was organized.

1. How do we understand the Higgs boson? What principle determines its couplings to quarks and leptons? Why does it condense and acquire a vacuum value throughout the

universe? Is there one Higgs particle, or many? Is the Higgs particle elementary or composite?

2. How do we understand the multiplicity of quarks and leptons? What principle determines their masses and mixings? Why is the mixing pattern apparently different for quarks and leptons? Why is the CKM CP phase nonzero? Is there CP violation in the lepton sector?

3. How do we understand the neutrinos? Why are their masses so different from those of other fermions? Are neutrinos their own antiparticles? Are their small masses connected to the presence of a very high mass scale? Are there new interactions invisible except through their role in neutrino physics?

4. How do we understand the matter-antimatter asymmetry of the universe? Why are the interactions of particles and antiparticles not exactly mirror opposites? What principle determines the excess of baryons over antibaryons that we see in the universe?

5. How do we understand the substance of dark matter? This is the dominant component of mass in the universe. What is the dark matter made of? Is it composed of one type of new particle or several? What principle determined the current density of dark matter in the universe? Are the dark matter particles connected to the particles of the Standard Model?

6. How do we understand the dark energy? Is it a static energy per unit volume of the vacuum, or is it dynamical and evolving with the universe? What principle determines its value?

7. How do we understand the origin of structure in the universe? The inflationary universe model requires new fields active in the early universe. Where did these come from, and how can we probe them today?

8. How do we understand the multiplicity of forces? Are there additional forces that we have not yet observed? Are there additional quantum numbers associated with new fundamental symmetries? Are the four known forces unified at very short distances? What principles are involved in this unification?

9. Are there new particles at the TeV energy scale? Such particles are motivated by the problem of the Higgs boson, and by ideas about spacetime symmetry such as supersymmetry and extra dimensions. If they exist, how do they acquire mass, and what is their mass spectrum? Do they carry new sources of quark and lepton mixing and CP violation?

10. Are there new particles at higher energies? Are there new invisible particles? Such particles are motivated by the strong CP problem, the problem of neutrino mass, the problem of the origin of cosmic inflation, the question of grand unification, and the

question of unification of microscopic forces with gravity. Can we learn the nature of these particles from our experiments?

The search for answers to these questions is intimately tied to the development of technology. High energy physics experiments and high energy accelerators put extraordinary demands on sensors, precision engineering, and data management, incorporated into devices of very large scale. Our community invents new technologies to address these needs and brings them into robust use. The progress of our field requires both technology development directed at the problems of specific experiments and the development of new technologies that allow leaps to higher performance or decreased cost for devices of broad application. This technology development for accelerators and detectors ultimately benefits all of physical science.

In many areas of physics experimentation, there are specific technological developments that would be of enormous benefit. Existing technologies are unlikely to meet the science needs of future high energy physics experiments. New technologies need to be explored that could lead to transformative advances, enabling cost-effective high energy physics experiments but also new initiatives of broad importance.

1. As experiments continue to reach for rarer processes, more precise measurements, higher energies and luminosities, and more inclusive observations, they place increasing demands on detector technology. How do we achieve the detectors of finer granularity, larger volume, greater radiation hardness, lower cost, and higher speed that will in large part determine our experimental reach?

2. Paradigm altering technology developments are occurring in electronics and materials design, potentially offering breakthrough capabilities. How can these advances be incorporated into new detectors with improved overall performance? How do we make best use of the resources available in universities, national laboratories and industry to develop new detector systems?

3. What technologies will be needed to acquire, analyze and store the enormous amounts of data from future experiments? Can local intelligence be incorporated to manage data flow? How will we fully and efficiently utilize data stored in large databases?

4. Scaling of current accelerator designs to higher energy leads to machines of very large size, cost, and power demand. Can new technologies lead to more practical strategies? Is there an ultimate highest energy for colliders?

5. Proposed experiments both at low and at high energy call for particle beams of extreme brightness. Are there technologies to achieve high beam power in a better controlled and more cost-effective way?