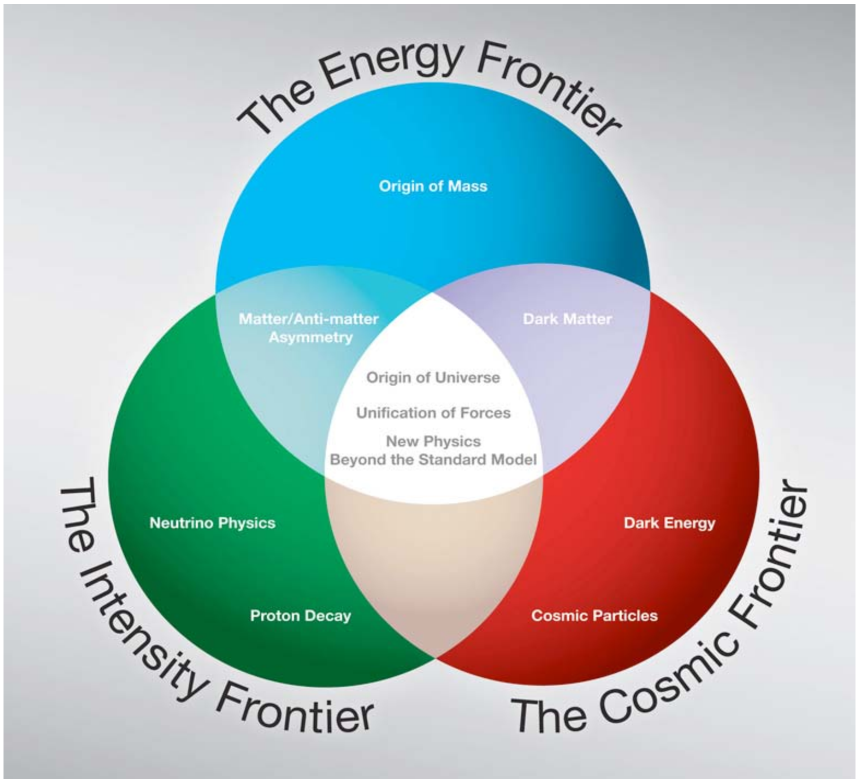
Major High Energy Physics Facilities
2014-2024

Input to the prioritization of proposed scientific user facilities for the Office of Science



HEPAP Facilities Subpanel

March 22, 2013

March 22, 2013

Dr. W. F. Brinkman
Director, Office of Science
Department of Energy
Washington, DC 20585

Dear Dr. Brinkman:

This letter is in response to your letter to the Chairs of the Office of Science Federal Advisory Committees, dated Dec. 20, 2012, (Appendix A) requesting help with the important task of prioritization of proposed scientific user facilities. In particular, this letter reports categorization of facilities in two areas, the ability of the facility to contribute to world-leading science in the next decade and the readiness of the facility for construction.

As suggested in your letter, I empanelled a special subpanel of HEPAP to collect input, assess facilities, and prepare this report. The Subpanel was broadly composed of accomplished physicists from a variety of backgrounds, representative of the demography of the field of high energy physics. It included physicists whose primary funding is provided by NSF, as well as those who are DOE funded. Appendix B lists the members of the Subpanel.

The Subpanel received an initial list of facilities to consider from the Office of High Energy Physics. It met to review this list and to organize its activities at the end of January, and since that time has held eight additional meetings. It collected written input from contacts established for each of the listed facilities. The input requested was in the form of a one to two page summary, addressing the facility's expected scientific impact and its construction readiness. An optional supporting note of less than ten pages, which could contain references to other material, was also provided by nearly all facilities. One of the Subpanel's meetings, held on February 13, 2013 at Fermilab, was a meeting open to the particle physics community and had the primary purpose of allowing the Subpanel to have questions addressed by the facility contacts. Accordingly, its agenda was organized as a very brief introduction of each facility followed by questions and answers regarding that facility. The agenda of this meeting is listed in Appendix C. (The Subpanel greatly appreciates the input and presentations prepared by the facilities contacts and their collaborators.) The open meeting was followed the next day by a face-to-face meeting of the Subpanel. The other subpanel meetings were held as teleconferences, which were supplemented by extensive email exchange.

The Subpanel's discussions were informed by previous reports of various advisory committees. Principal among these is:

US Particle Physics: Scientific Opportunities
A Strategic Plan for the Next Ten Years
Report of the Particle Physics Project Prioritization Panel;
29 May 2008

which has guided the US HEP program for the last five years. Other important reports and studies that bear upon the facilities considered in this letter report include:

- High-Energy Physics Facilities for the DOE Office of Science Twenty-Year Roadmap (2003);
- Report of the HEPAP Particle Astrophysics Scientific Assessment Group (PASAG) (2009);
- An Assessment of the Science Proposed for the Deep Underground Science and Engineering Laboratory (DUSEL); Ad Hoc Committee to Assess the Science Proposed for the Deep Underground Science and Engineering Laboratory (DUSEL); Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Research Council of the National Academies (2011);
- New Worlds, New Horizons in Astronomy and Astrophysics; Committee for a Decadal Survey of Astronomy and Astrophysics; Board on Physics and Astronomy; Space Studies Board; Division on Engineering and Physical Sciences; National Research Council of the National Academies (2010);
- LBNE Reconfiguration; Steering Committee Report (2012); and
- Proposed Update of the European Strategy for Particle Physics; Erice (2013).

Preliminary conclusions of the Subpanel's assessments were presented to HEPAP at its meeting on March 11, 2013. Since that meeting, the Subpanel completed drafting of the letter report, and the report was approved by HEPAP.

The main body of our letter report starts in the next sections with the list of the fundamental questions that drive the field of particle physics, remarks upon the HEP roadmap process, list of the facilities considered, and remarks upon the categories used. The main body of the report, the description of the outcome of the categorization process for each facility considered, follows. As directed by the charge, no rank ordering of the facilities is provided. For each facility, a one-page description of the facility and its science goals is provided in Appendix D.

Science questions that drive the field of particle physics

Particle physics strives to discover the answers to fundamental questions about nature and the Universe by probing the smallest and largest scales. In 2008, a HEPAP subpanel, the Particle Physics Project Prioritization Panel (P5), outlined a strategic plan, a "roadmap", for U.S. particle physics growing out of nine questions set forth by "The Quantum Universe: The Revolution in 21st Century Particle Physics; DOE/NSF High Energy Physics Advisory Panel Quantum Universe Committee" and taking them as a mission statement for the field:

1. Are there undiscovered principles of nature: new symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

In the course of developing the roadmap for a leadership role for the U.S. in world-wide particle physics, P5 created a view centered around three differing approaches in particle physics, labeling them as *frontiers*. The questions above and the intellectual framework of particle physics flow across the frontiers, and this division recognizes the strength of different perspectives on the same problems. The Energy Frontier seeks understanding of known phenomena and searches for new phenomena through particle collisions at the highest technically achievable energies. The Intensity Frontier makes precision measurements of known processes seeking a discrepancy with precise calculations and seeks to produce rare events not predicted by current theory. The Intensity Frontier also allows the study of neutrino oscillations and other neutrino properties. The Cosmic Frontier uses the techniques of astronomy and astrophysics to observe processes in conditions not possible on Earth, as well as particle and other techniques in underground and surface facilities, and seeks to interpret these observations in terms of new particles and/or new interactions. The P5 roadmap and frontier configuration was endorsed by HEPAP and has guided the thinking of the community. Recent years have seen important progress in each of the three frontiers: observation of a particle likely to be the Higgs boson at the LHC, measurement of $\sin^2 2\theta_{13}$ in neutrino oscillation experiments, and important new limits on dark matter and on neutrino-less double beta decay.

HEP roadmap

These and other important experimental results have inspired new experiments as well as refined approaches by current and proposed experiments. This report of the present subpanel on facilities, in response to your charge, will be part of an overall prioritization in the DOE Office of Science and represents a snapshot of the major facilities of the field of particle physics. Following the charge, we considered only experiments and facilities that are within a ten-year time horizon and are expected to cost over $100M; consequently, this report is necessarily incomplete. The main planning effort for the field lies in the coming months. The particle physics community, led by the APS Division of Particles and Fields, initiated a community planning process in 2012 that involves a nearly year-long series of workshops and that will culminate in a report of its study of scientific opportunities in the coming 10-20 years. This community planning and report will lay the foundations for an update of the HEP roadmap via a new project prioritization process, with which DOE and NSF are anticipated to charge a HEPAP P5 subpanel in the second half of 2013.

List of facilities considered

As directed by the charge, we considered only those facilities that require a minimum investment of $100 million, where we have treated this minimum as the Office of Science investment in cases of interagency or international facilities. In light of the 10-year horizon of this assessment, we considered only those facilities that would initiate construction (applied as being ready for consideration for CD-1 approval) by 2024. We did not include a number of other facilities that we discussed, including a circular electron-positron collider for precision studies of the Higgs boson and other phenomena, for one or the other of the above criteria.

The list of facilities considered is:

- Facilities with CD-1 approval:
  - Mu2e (IF)
  - LBNE (IF)
  - LSST (CF)
- Facilities in an advanced stage of development:
  - High-Luminosity upgrade of LHC (EF)
    - Accelerator upgrade for the HL-LHC
    - ATLAS upgrade for the HL-LHC
    - CMS upgrade for the HL-LHC
  - International Linear Collider (hosted in Japan) (EF)
    - ILC accelerator
    - ILC detectors
  - Project X accelerator (IF)
- Facilities in conceptual development & next-generation facilities:
  - New Project X experiments (IF)
  - nuSTORM (IF)
  - Third generation direct detection dark matter experiment(s) (CF)
  - Next generation dark energy experiment (CF)

For purposes of presentation, the facilities are listed above in categories that crudely characterize the facility's phase of development. The experimental frontier to which each facility belongs is denoted by the designations: [CF] Cosmic Frontier, [EF] Energy Frontier, [IF] Intensity Frontier. An additional facility that is of great scientific interest to the particle physics community, a ton-scale neutrino-less double beta decay experiment, is being considered as part of the NSAC facilities assessment because NP is its steward; consequently, this facility is not considered in this report.

HEP facilities are of two basic types, accelerator facilities and detector facilities. Accelerator facilities provide particle beams for multiple experiments, big and/or small. The present Fermilab accelerator complex and the LHC are examples of accelerator facilities. The accelerator facilities on the list considered are the accelerator upgrade for the HL-LHC, the ILC accelerator, and the Project X accelerator.

Detector facilities are used to perform experiments, *i.e.*, to conduct a research program. Detector facilities are built, and maintained and operated, by collaborations of scientists involved in the research program. These collaborations can consist of hundreds or even thousands of scientists. Large detector facilities are typically built using resources from multiple and international funding agencies. The CDF and D0 detectors that operated at the Fermilab Tevatron and the ATLAS and CMS detectors that presently operate at the CERN LHC are examples of detector facilities. They are facilities in the sense that they serve many users and typically address multiple science questions.

The accelerator and detector facilities funded by the Office of High Energy Physics generally serve a large community of both DOE and NSF supported particle physicists, as well as scientists from other nations. Some of these facilities also serve significant numbers of scientists from other fields, most notably from nuclear physics and from astrophysics.

The scale and technical challenges of the accelerators and detectors to probe deeper and deeper into the particle world and further and further into the Universe increasingly demand international, or even global, collaboration. For instance, the LHC accelerator and detectors were built at CERN by its many member states with substantial, and critical, contributions from Japan, Russia, and the U.S. The technical development of the ILC accelerator and detectors has been conducted as a global initiative.

The facilities on the above list reflect a number of characteristics of experimental particle physics. They reflect the diversity of tools and techniques, including the three frontiers but also a variety of techniques within each frontier, that are required to address the challenging central science questions of the field. They reflect the extensive time from conception through construction demanded to address the scale and challenge of the detectors required by the science; all but one of the facilities listed above are part of the 2008 P5 roadmap, and nearly all were included in the 2003 HEP facilities 20-year roadmap (reported in response to a similar charge from the Office of Science). They also reflect the multi-generational approach to addressing the most profound questions of the field by reaching further and probing deeper on each frontier, where each generation is based upon the progress and results of its predecessors. Indeed, within the field, a number of high-energy physics facilities have ceased operation in the last decade as more capable facilities have been brought online. Finally, the list of facilities reflects the fact that some large facilities are based in the U.S. and some involve U.S. participation in facilities abroad.

Scientific progress in particle physics requires access to and intellectual contributions by U.S. scientists to central science facilities abroad, as well as offering facilities in the U.S. that fit the global program and that serve the worldwide scientific community, while providing intellectual opportunity within the U.S. This model of access and contribution has worked well in the past, although it is becoming more challenging as the size of facilities grows and the number of facilities shrinks; nevertheless, the LHC demonstrates the success of this model.

Categorization of facilities

We assess "the ability of the facility to contribute to world-leading science" and we place each facility in one of four categories provided by the charge: (a) *absolutely central*; (b) *important*; (c) *lower priority*; and (d) *don't know enough yet*. In order to be categorized as *absolutely central*, we require that: (1) the science question or questions to be addressed by the facility must be among the questions of very great scientific importance for the field of particle physics, questions whose answers have the potential to change our view of the; (2) the facility must very significantly improve upon the capabilities of existing facilities to address the scientific questions; and (3) the facility must be unique in its capabilities. In order to be categorized as *important*, we continue to require that question(s) to be addressed are of very great scientific importance; and we require that the facility must significantly improve upon the capabilities of existing facilities.

We assess "the readiness of the facility for construction" and we place each facility in one of three categories provided by the charge: (a) *ready to initiate construction*; (b) *significant scientific/engineering challenges to resolve before initiating construction*; and (c) *mission and technical requirements not yet fully defined*. In order to be categorized as *ready to initiate construction*, we require that a facility must be at a level of technical maturity to allow proceeding to the project engineering and design stage, which, in terms of the critical decision process, means ready to proceed to CD-1 approval. Because of the coarseness of the available categories, we categorize facilities that are not yet ready to initiate construction and whose mission and essential technical requirements are fully defined as *significant scientific/engineering challenges to resolve before initiating construction* regardless of how significant or how challenging the remaining research and/or development is.

Energy Frontier facilities

Accelerator upgrade for the HL-LHC
ATLAS upgrade for the HL-LHC
CMS upgrade for the HL-LHC

The Large Hadron Collider (LHC) provides the world's highest center-of-mass energy collisions. The facility just completed a successful first run, providing approximately 5 fb^{-1} and 25 fb^{-1} of luminosity at center-of-mass energies of 7 TeV and 8 TeV, respectively, to each of the two general purpose detectors, ATLAS and CMS. The next LHC run is scheduled to begin in 2015 and is projected to deliver center-of-mass energies in excess of 13 TeV, with a delivered luminosity of 300 fb^{-1} by early 2022. Another shutdown is scheduled for 2022-23, during which time substantial upgrades to the LHC and to both experiments, ATLAS and CMS, will be installed. U.S. participation in three facilities is associated with the upgrade: accelerator upgrades for the High-Luminosity LHC (HL-LHC); the ATLAS upgrade to operate at HL-LHC; and the CMS upgrade to operate at HL-LHC. The accelerator upgrade will increase integrated luminosity to the experiments by a factor of ten with respect to the integrated luminosity anticipated before the upgrade (a factor of 100 with respect to present). The associated large data sample and the ATLAS and CMS upgrades will support a diverse particle physics program. Measurements of the properties of the Higgs boson will be substantially improved, and the data sample will enable the study of rare decays of the Higgs as well as of the top quark. If new physics is discovered in the period before the upgrade, the samples available to explore that physics will be greatly enhanced at the HL-LHC. The reach for new physics will also be increased, both by probing higher mass scales and by exploring processes with smaller production cross sections. U.S. scientists will contribute critical expertise and experience to the accelerator upgrade and to the upgrade of both ATLAS and CMS, and to the ensuing research program, as they have for the current facilities. U.S. participation in all three upgrades is almost certain to be required for continued participation of U.S. scientists in the international experiment collaborations. In this era, the LHC, and the ATLAS and CMS upgrades, will also serve a significant number of scientists from the U.S. nuclear physics community who study relativistic heavy ion collisions at the LHC. The accelerator upgrade for the HL-LHC will deliver the large data samples that fuel the HL-LHC research program; it is *absolutely central*. Although the technologies needed for the accelerator upgrade have been proven, there remain *significant scientific/engineering challenges to resolve before initiating construction*. The ATLAS and CMS upgrades are required to maintain the present capabilities of the detectors in the high luminosity environment of the HL-LHC, and thus to enable the HL-LHC research program. The two experiments complement and reinforce each other, and the results of the two experiments can be combined to improve statistically limited measurements. Both the ATLAS upgrade for the HL-LHC and the CMS upgrade for the HL-LHC are *absolutely central*. The detector technologies required for the ATLAS and CMS upgrades exist; however, designs are not yet ready to initiate construction, and for this reason the readiness classification *significant scientific/engineering challenges to resolve before initiating construction* is assigned to both ATLAS and CMS upgrades.

International Linear Collider (hosted in Japan) - Accelerator
International Linear Collider (hosted in Japan) - Detectors

The discovery of the Higgs boson reinforces the strong scientific case for the International Linear Collider (ILC). The ILC research program will be complementary to the research program of the LHC (and HL-LHC), in that it can deliver measurements that are complementary, as well as enable searches for new physics that are complementary to those performed at the LHC. For instance, the ILC enables high precision measurements of Higgs boson properties in a program complementary to the LHC. Beginning at energy above the threshold for production of pairs of top quarks, the ILC will allow a detailed study of top physics, which is closely connected to the phenomenon of electroweak symmetry breaking. Through precision measurements, the ILC will be a sensitive probe of new physics, such as that from additional gauge bosons and extra dimensions at high mass scales. The ILC accelerator and detectors enable a research program that will address questions of very great scientific importance, and both the accelerator and the detectors are *absolutely central*. The initiative from the Japanese particle physics community to host the ILC in Japan is very welcome, and the U.S. particle physics community looks forward to a proposal from Japan to discuss possible participation. The ILC accelerator has been the subject of a comprehensive international development program with significant U.S. contributions and leadership roles. A technical design report for the accelerator facility was recently completed; the ILC accelerator is technically *ready to initiate construction* once agreements are reached in Japan and internationally. Detailed baseline designs for the detectors have been completed; however, engineering remains before the ILC detectors are ready to initiate construction, and for this reason the readiness classification *significant scientific/engineering challenges to resolve before initiating construction* is assigned.

Intensity Frontier facilities

Mu2e

Understanding the source of lepton flavor violation is a question of very great scientific importance. The discovery of neutrino mixing established that lepton flavor is not conserved; however, flavor violation in the charged lepton sector has not yet been observed. The Mu2e experiment will search for the conversion of a muon to an electron in the field of a nucleus and will improve the limits on flavor violation in muon interactions by four orders of magnitude and reach a sensitivity where a positive signal would be expected in many models. The Mu2e experiment is *absolutely central*. The project has CD-1 approval and is therefore classified as *ready to initiate construction*.

LBNE

The 2008 P5 report recommended a world-class neutrino program as a core component of the US HEP program. This report envisioned a large detector underground targeted by a high intensity neutrino beam and that would be capable of a broad physics program including the study of neutrino oscillations in order to resolve the neutrino mass hierarchy, to search for CP violation in the neutrino sector, and to search for new physics in neutrino oscillations, while contributing also to the search for proton decay and to measurements of neutrinos from galactic supernovae. The 2010 NRC assessment of the Deep Underground Science and Engineering Laboratory (DUSEL) characterized the neutrino experiment as "an exceptional opportunity to address scientific questions of paramount importance", and characterized its sensitivity to the study of proton decay and to detection of supernova neutrinos as "of great scientific interest". The first stage of the Long Baseline Neutrino Experiment (LBNE) initiates the program toward that long term goal. In this stage, a new neutrino beam line, initially to be operated at 700 kW, but capable of 2.3 MW, will be constructed at Fermilab and directed towards a new massive high-sensitivity neutrino detector at the Homestake mine. LBNE will bring several unique features to the future study of neutrino oscillations; its baseline will be the longest in the world, it will study oscillations over the broadest range of neutrino energies, and it will advance the technology of neutrino detection. This stage of LBNE will make significant advances in the measurement of the neutrino mass hierarchy and begin the search for CP violation in neutrinos. Additional participation from international collaborators could significantly extend the science program of this first stage. The first stage of LBNE is *important* and it lays the foundations for the *absolutely central* world-class neutrino program envisioned by P5. The first stage has CD-1 approval and is therefore classified as *ready to initiate construction*.

PROJECT X accelerator
PROJECT X experiments

The Project X accelerator facility is an evolution of the Fermilab accelerator complex that can simultaneously produce high-intensity beams of various particle species (*e.g.,* neutrinos, muons, kaons) to support a suite of Project X experiments studying a broad range of science questions. The Project X accelerator would be a world-leading facility for supporting a broad Intensity Frontier research program, and would be capable of providing beams with unique characteristics required by specific experiments. In addition to enabling new experiments, the Project X accelerator facility would dramatically enhance the physics capabilities of some existing and proposed experiments, including the Mu2e and LBNE facilities. The full Project X research program is currently in the planning stage, and includes a spallation target optimized for particle physics applications.

The Project X accelerator facility can be deployed in stages, with each successive stage introducing new world-class research capability and each stage retiring significant legacy elements of the Fermilab accelerator complex. The Project X accelerator facility and the associated spallation target have potentially broader impacts beyond particle physics as a resource to the nuclear physics, material science, and fusion energy communities. The fusion energy community for instance identified a “Materials Facilities Initiative” utilizing a spallation target as absolutely central to Fusion Energy Science.

The development of Project X was endorsed by the 2008 P5 report, which recommended an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab. The importance and breadth of the research program that it enables and enhances, leads the Project X accelerator facility to be classified as *absolutely central*. Although R&D is still required for the spallation target needed by some experiments, all stages of the Project X accelerator facility are *ready to initiate construction.*

Project X experiments that compose the research program range from important to absolutely central, but scientifically the Project X research program as a whole is classified as *absolutely central*. Being in the planning phase, the construction readiness of the Project X research program is classified as *mission and technical requirements not yet fully defined*, although some experiments are beyond this phase.

nuSTORM

nuSTORM would be a unique neutrino facility based on a muon storage ring that would provide neutrino beams with well-defined flavor composition and spectrum. It would also serve as a valuable platform for developing muon storage ring technology. nuSTORM would be superb for measuring neutrino cross sections and for exploring anomalies observed in prior short baseline neutrino experiments. nuSTORM is still in the early stages of planning, and while a proposal is planned for June 2013, neither a proposal nor a design report is currently available. At this time, we classify the scientific capabilities of nuSTORM as *don’t know enough yet.* While we are not aware of significant technical challenges facing nuSTORM, we are unable to evaluate construction readiness based on the currently available information and classify it as *mission and technical requirements not yet fully defined*.

Cosmic Frontier facilities

Third Generation Direct Detection Dark Matter Experiment(s) (DM-G3)

Detection of dark matter presents one of the greatest experimental challenges of all time, and definitive detection will rely in successful integration of results from nuclear recoil experiments (often referred to as direct detection), the LHC, as well as astrophysical and astronomical measurements (often referred to as indirect detection). The nuclear recoil technique for searching for dark matter has improved in sensitivity over the last twenty-five years by a factor of ten billion, about a decade of sensitivity every two and a half years. This technique, in which the recoil energy of a nucleus struck by a dark matter particle is measured two or more different ways, has been applied to gas, liquid, and solid target media, and it has currently achieved thresholds of a few keV, critical for high detection efficiency. Presently, DOE and NSF have a well defined roadmap of second followed by third generation detectors that will provide increasingly greater sensitivity in coupling over a wide range of possible dark matter masses. The second generation of detectors, which are presently under development, will probe couplings comparable to those accessible to the LHC. The third generation would improve sensitivity by an order of magnitude. Owing to the difficulty of the measurement, at least two detectors will be needed to establish a result. Third generation dark matter nuclear recoil detectors are *absolutely central*. The third generation of detectors has *significant scientific/engineering challenges to resolve before initiating construction*.

LSST

The Nobel Prize for Physics in 2011 was awarded for the discovery of the accelerating expansion of the Universe, but the basic question “Why is the expansion speeding up?” remains unanswered. The Large Synoptic Survey Telescope (LSST) is an 8.4-meter telescope with a 3-Gigapixel camera that, over 10 years starting early in the next decade, will carry out deep, wide imaging surveys of the southern sky. While of interest to a broad astronomy and astrophysics community, addressing the fundamental questions about cosmic acceleration is among the primary scientific objectives of the LSST. LSST is the central next-generation component in the DOE OHEP program to explore dark energy. It will measure the cosmic expansion history and growth of structure in the Universe through measurements of supernovae, weak and strong gravitational lensing, large-scale galaxy clustering, and clusters of galaxies. Its ability to contribute to world-leading science is *absolutely central*. The LSST telescope project has been approved by the National Science Board for MREFC funding at NSF, and the LSST camera project has been awarded CD-1 approval by DOE. LSST is therefore classified as *ready to initiate construction*.

Next Generation Dark Energy Experiment

The discovery that the expansion of the Universe is speeding up engendered a progressive program of U.S.-led Cosmic Frontier experiments that will probe dark energy and the physical origin of cosmic acceleration with increasing precision. Determining the ultimate nature and properties of dark energy and the physical cause of cosmic acceleration is challenging and requires multiple techniques and facilities. The Next Generation Dark Energy Experiment embodies the recognition that a future facility complementary to LSST will be necessary to more fully address these fundamental questions. Examples of such an experiment include: WFIRST (Wide-Field Infrared Space Telescope), a proposed NASA space mission; a large-aperture (8-10m) ground-based telescope that could carry out deep, wide spectroscopic redshift surveys of LSST targets; and 21-cm intensity mapping radio observations to measure baryon acoustic oscillations. A next-generation dark energy facility would be world-leading and, given the importance of the fundamental questions that it would address (such as the nature of 70% of the Universe) it is *absolutely central*. The readiness of the facility depends upon which facility concept is pursued; consequently, the construction readiness of the next generation dark energy experiment is classified as *mission and technical requirements are not yet fully defined*.

Conclusion

The facilities characterized above as *important* and as *absolutely central* are those facilities that are required in order to address the critical scientific questions of the field of particle physics. Together these facilities will constitute the integrated program on the three frontiers of the field, Energy, Intensity, and Cosmic, that will lead to the discoveries that will propel the field forward in its understanding of physics on both the smallest and largest scales. These facilities provide for a program that progressively reaches further and probes deeper, and where each subsequent step is informed by the progress of its predecessors. These facilities also reflect the international, and increasingly global, character of the field of particle physics, as they reflect U.S. facilities and participation in facilities outside the U.S. in the context of a worldwide program.

Respectfully,

Andrew J. Lankford

Andrew J. Lankford
Chair, HEPAP

cc: Patricia Dehmer
James L. Siegris

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

December 20, 2012

To: **Chairs of the Office of Science Federal Advisory Committees:**
Professor Roscoe C. Giles, ASCAC
Professor John C. Hemminger, BESAC
Professor Gary Stacey, BERAC
Professor Martin Greenwald, FESAC
Professor Andrew J. Lankford, HEPAP
Dr. Donald Geesaman, NSAC

From: **W. F. Brinkman**
Director, Office of Science

I am writing to present a new charge to each of the Office of Science Federal Advisory Committees. I would like each Advisory Committee to help us with an important task—the prioritization of proposed scientific user facilities for the Office of Science. To meet a very compressed timetable, **we will need your final report by March 22, 2013**.

This charge derives from Administration efforts to improve the efficiency, effectiveness, and accountability of government programs and requirements of the Government Performance and Results Modernization Act of 2010. In order to improve the agency's performance, and in compliance with this Act, DOE has established several Priority Goals, including the following goal for the Office of Science:

> *Goal Statement: Prioritization of scientific facilities to ensure optimal benefit from Federal investments. By September 30, 2013, formulate a 10-year prioritization of scientific facilities across the Office of Science based on (1) the ability of the facility to contribute to world-leading science, (2) the readiness of the facility for construction, and (3) an estimated construction and operations cost of the facility.*

To accomplish this goal, DOE will undertake the following steps. We will need your help with step #2, as described below.

1. *The DOE/SC Associate Directors will create a list of proposed new scientific user facilities or major upgrades to existing scientific user facilities that could contribute to world leading science in their respective programs from 2014 to*

2024 (the timeframe covered by this goal).

This step is complete. The Associate Directors have developed material describing the nature of a number of proposed new or upgraded facilities, the scientific justification for the facility or upgrade, and the various inputs from the scientific community that provided motivation for the proposal. Additionally, the Associate Directors have provided assessments of their existing scientific user facilities to contribute to world-leading science through 2024. The Associate Directors will be in touch with their respective FACA chairs shortly to submit this material directly to you.

2. *The information developed by the DOE/SC Associate Directors will be used by the DOE/SC as the basis for engagement with the DOE/SC Federal Advisory Committees and others to seek advice and input on new or upgraded scientific user facilities necessary to position the DOE/SC at the forefront of scientific discovery. The Federal Advisory Committees will seek additional outside input as necessary. In particular, for programs that have a significant existing or potential user base outside of the DOE/SC, the Federal Advisory Committees will be encouraged to seek input from the broader scientific community and existing facility user committees.*

   In order for your Advisory Committee to execute step #2, I suggest that you empanel a subcommittee to review the list of existing and proposed facilities provided to you by the program Associate Director, subtracting from or adding to the list as you feel appropriate. To address the concerns of the broad facilities user community, the subcommittees should include representatives of the broad, multi-disciplinary community that stands to benefit from these facilities, including representatives whose research is supported by other Federal agencies. In its deliberations, the subcommittees should reference relevant planning documents and decadal studies. If you wish to add facilities or upgrades, please consider only those that require a minimum investment of $100 million. More detailed instructions for the report are given below.

3. *Finally, with input from the DOE/SC Federal Advisory Committees and other stakeholders, the DOE/SC Director will prioritize the proposed new scientific user facilities and major upgrades across scientific disciplines according to his/her assessment of the scientific promise, the readiness of the facility to proceed to construction, and the cost of construction and operation. In making this prioritization, the DOE/SC Director will consider the resource needs for research support and for robust operation of existing facilities and will engage leaders of other relevant agencies and the Administration to ensure priorities are coordinated with related investments by other agencies and reflect cross-agency needs where appropriate.*

Please provide me with a short letter report that assigns each of the facilities to a category and provides a short justification for that categorization in the following two areas, but do not rank order the facilities:

1. *The ability of the facility to contribute to world-leading science in the next decade (2014 – 2024)*. Please include both existing and proposed facilities/upgrades and consider, for example, the extent to which the proposed or existing facility or upgrade would answer the most important scientific questions; whether there are other ways or other facilities that would be able to answer these questions; whether the facility would contribute to many or few areas of research and especially whether the facility will address needs of the broad community of users including those supported by other Federal agencies; whether construction of the facility will create new synergies within a field or among fields of research; and what level of demand exists within the (sometimes many) scientific communities that use the facility. **Please place each facility or upgrade in one of four categories: (a) absolutely central; (b) important; (c) lower priority; and (d) don't know enough yet.**

2. *The readiness of the facility for construction*. For proposed facilities and major upgrades, please consider, for example, whether the concept of the facility has been formally studied; the level of confidence that the technical challenges involved in building the facility can be met; the sufficiency of R&D performed to-date to assure technical feasibility of the facility; and the extent to which the cost to build and operate the facility is understood. **Please place each facility in one of three categories: (a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; and (c) mission and technical requirements not yet fully defined.**

Each SC program Associate Director will contact the Chair of his or her Federal Advisory Committee to discuss and coordinate the logistics of executing this charge. We realize that the six SC programs will require somewhat different approaches, in part based on recent and future community planning activities. In addition, if you would like to discuss the charge further, please feel free to contact Pat Dehmer (patricia.dehmer@science.doe.gov). Thank you for your help with this important task.

Appendix B

Members of the HEPAP Facilities Subpanel

Andy Lankford,	*UC Irvine (chair)*
Sally Dawson,	*BNL*
Peter Fisher,	*MIT*
Joshua Frieman,	*Chicago/Fermilab*
Stuart Henderson,	*Fermilab*
Norbert Holtkamp,	*SLAC*
Mark Messier,	*Indiana U.*
Ritchie Patterson,	*Cornell*
Regina Rameika,	*Fermilab*
Marjorie Shapiro,	*UC Berkeley/LBNL*
Robert Tschirhart,	*Fermilab*
Andrew White,	*U. Texas, Arlington*
Mark Wise,	*Caltech*

Appendix C

Agenda
HEPAP Facilities Subpanel Face-to-Face Meeting
February 13, 2013 Fermilab

https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=6381

9:00	9:15	**INTRODUCTION**	A.J. Lankford (UC Irvine)
9:15	9:45	**INTENSITY FRONTIER SESSION**	
		9:15 **nuSTORM**	Alan Bross (Fermilab)
		9:25 Q&A	
		Project X	
		9:45 **Project X Research Program**	Andreas Kronfeld (Fermilab)
		10:05 Q&A	
		10:25 **Project X Accelerator**	Stephen Holmes (Fermilab)
		10:33 Q&A	
11:15	12:20	**COSMIC FRONTIER SESSION**	
		11:15 **Third Generation Dark Matter**	Bernard Saduoulet (Berkeley)
		11:25 Q&A	
		11:45 **LSST**	Steve Kahn (SLAC)
		11:55 Q&A	
		12:15 **Next Generation Dark Energy** This facility will be discussed at a future subpanel meeting.	
12:20	13:20	Lunch	
		ENERGY FRONTIER SESSION	
		13:20 **HL-LHC - accelerator**	Eric Prebys (Fermilab)
		13:30 Q&A	
		13:50 **HL-LHC - ATLAS**	Michael Tuts (Columbia)
		14:00 Q&A	
		14:20 **HL-LHC - CMS**	Joel Butler (Fermilab)
		14:30 Q&A	
		14:50 **ILC (hosted in Japan) - Physics & Detectors**	James Brau (Oregon)
		15:02 Q&A	
		15:26 **ILC (hosted in Japan) - Accelerator**	Mike Harrison (BNL)
		15:34 Q&A	
		15:50 **Higgs Factory** This facility will be discussed at a future subpanel meeting.	
15:55	17:15	Break	
17:15	18:15	**INTENSITY FRONTIER SESSION - ii**	
		17:15 **Mu2e**	Ron Ray (Fermilab)
		17:25 Q&A	
		17:45 **LBNE**	Robert Wilson (Colorado State)
		17:55 Q&A	
18:15	19:15	**DISCUSSION**	
19:15	21:30	Reception	

Appendix D

One-Page Summaries of HEP Facilities

LHC Accelerator Upgrades

Description: The Large Hadron Collider (LHC) at CERN is the world's highest energy collider, presently operating at 4 TeV per beam, with plans in place to reach energies of at least 6.5 TeV per beam within two years. The LHC and its two detectors, CMS and ATLAS, were constructed as an international project with substantial involvement of U.S. scientists and engineers. Through these contributions the U.S. has been able to play leading roles in exploiting the scientific capabilities of the LHC through the involvement and leadership of U.S. scientists in ATLAS and CMS.

To fully capitalize on the substantial worldwide investments in the LHC, it will be necessary to upgrade the accelerator in the next decade. The most cost-effective approach to increase the scientific productivity is to increase the particle beam collision frequency, or luminosity. At the end of this decade, after a series of improvements are implemented, the peak luminosity should reach $2 \times 10^{34} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$. The luminosity can be increased to $5 \times 10^{34} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$, resulting in an integrated luminosity of ~250 fb^{-1}/year, through a series of upgrades to the LHC and its injector systems which are planned to be implemented in 2022. This large increase in luminosity will greatly extend the sensitivity of the physics studies and make accessible important channels that have very small production rates.

The key to increasing the luminosity will be to focus the beams to smaller sizes at the collision point. Achieving this will require replacing the superconducting quadrupole magnets nearest the interaction point with new magnets having higher field gradient and aperture. The requirements go beyond the capability of NbTi, and require constructing magnets based on Nb_3Sn superconductor, which has been a focus of DOE/HEP-funded magnet R&D (through LARP, the LHC Accelerator Research Program) for the past decade. As a result, the US is the undisputed world leader in this area. The proposed US contribution is to complete R&D leading to a Nb_3Sn prototype, and then to produce half of the required cold masses for the upgrade, while transferring the technology to CERN, who will build the remaining cold masses and cryostats.

It will become necessary to compensate for the finite crossing angle of the two proton beams at the collision point in order to maximize the luminosity. The preferred scheme utilizes superconducting radiofrequency deflecting cavities ("crab" cavities) to introduce a position-dependent lateral deflection such that the bunches collide head-on. Again, LARP has been a leader in this area. The US contribution includes cryostated crab cavity prototypes and then production of all the required cavities and cryostats. The final US contribution will be a high bandwidth feedback system to compensate for intensity and brightness effects in the SPS, and possibly other accelerators in the system.

Science: The LHC accelerator upgrades enable a robust physics program that has been proposed to utilize up to 3000 fb^{-1} at ~14 TeV center-of-mass energy. These upgrades are required to reach this integrated luminosity in a reasonable amount of data-taking time.

Collaboration: The proposed U.S. scope is tightly integrated with CERN, with both sides providing significant resources to the upgrade project. In models currently being discussed, in the case of the magnets, CERN would provide half of the cold masses and all cryostats and power supplies. For the crab cavities, CERN would provide the power couplers and infrastructure. For the feedback system, CERN would provide all vacuum components.

Science Classification and Readiness: The accelerator upgrade for the HL-LHC will deliver the large data samples that fuel the HL-LHC research program; it is *absolutely central*. Although the technologies needed for the accelerator upgrade have been proven, there remain *significant scientific/engineering challenges to resolve before initiating construction*.

ATLAS Upgrade to Operate at the HL-LHC

Description: The High Luminosity LHC (HL-LHC) is expected to begin operating in 2024, providing proton-on-proton collisions at a center-of-mass energy of ~14 TeV and a levelled instantaneous luminosity of 5×10^{34} cm^{-2} s^{-1}. The aim of the program is to deliver a total of 3000 fb^{-1}, an order-of-magnitude increase over the projected integrated luminosity for the pre-2024 period. This increase in size of the data sample will significantly enhance the physics reach of the ATLAS experiment. The primary detector challenges in the HL-LHC environment are to maintain high performance in vertex and track reconstruction, lepton identification and heavy flavor tagging. These will be addressed via three fundamental detector improvements: a complete replacement of the current tracking system; an upgraded Trigger and Data Acquisition (TDAQ) architecture that will handle the increased rates; and new radiation-hard readout electronics using state-of-the art technologies for the tracker, calorimeter and muon detector systems. The proposed all-silicon tracker design will use modern sensors and radiation-tolerant ASIC technology which, along with its improved geometrical acceptance and reduced upstream material, will provide superior performance when compared to the current tracker, even at the anticipated 200 interactions per-crossing in the HL-LHC environment. The upgraded detector readout systems and TDAQ architecture are motivated by the desire to maintain low trigger thresholds and adequate bandwidth in order to maximize physics acceptance. The computing and software of the experiment must also evolve to meet the needs of the upgraded detector systems.

Science: The high luminosity at the HL-LHC extends the energy scale accessed via high energy boson-boson scattering, allows enhanced studies of the electroweak symmetry breaking mechanism, and probes new physics predicted by models such as SUSY and extra dimensions well into the multi-TeV region. The range of new physics signatures includes: searches for high mass gauge bosons, reconstruction of complex SUSY cascade decays and searches for resonances in top-quark pairs. In July 2012, the ATLAS and CMS experiments announced the discovery of a Higgs boson candidate with a mass of about 125 GeV. The luminosity available to the HL-LHC will allow ATLAS to measure this particle's properties with the highest possible precision, testing the validity of the Standard Model. The large data sample will allow the measurement of the Higgs couplings to other particles to a precision of 5% to 30%, depending on particle type. The increased data set will also enable probes of rare decays such as $H\rightarrow\mu\mu$, of vector boson fusion production of $H \rightarrow tt$ and $H \rightarrow \gamma\gamma$, and of associated Higgs production with a top-pair. These additional channels increase the precision with which the fermion couplings can be measured, and improve the limits on new physics that can be set from loops. The full luminosity will also allow the Higgs self-coupling to be studied for the first time, in channels such as $HH \rightarrow ttbb$ and $HH \rightarrow \gamma\gamma bb$.

Collaboration: The ATLAS experiment is a global effort. The U.S. physicists come from 44 U.S. institutes, including four national laboratories, and comprise about 20% of the ATLAS collaboration, which consists of 2,500 physicists from 178 institutions in 38 countries. U.S. ATLAS is currently funded by both the DOE and the NSF. U.S. ATLAS Groups have played key roles in the construction, operation, and physics analysis in the past, and are anticipated to do so in the future.

Science Classification and Readiness: The science to be produced by the ATLAS Upgrade to operate at the HL-LHC is *absolutely central*. ATLAS has just published a Letter of Intent for this upgrade. The detector technologies required for the upgrade exist. The U.S. is actively pursuing the R&D for the new silicon tracker and the upgrade of the readout electronics in order to address the remaining s*ignificant scientific/engineering challenges to resolve before initiating construction.*

CMS Upgrade to Operate at the HL-LHC

Description: The HL-LHC will operate at 14 TeV center-of-mass energy with a peak luminosity of $5 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ and luminosity leveling. To exploit the very high interaction rate and integrated luminosity, reaching 3000 fb^{-1}, major upgrades to CMS are necessary. The goal is to achieve a physics efficiency at this higher luminosity (and pileup) that is at least as good as that achieved in the current detector at $10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$. These upgrades would be installed in the long shutdown scheduled for 2022-23. The HL running is expected for 2024-2036.

The tracking system must be completely replaced with one with much higher granularity (hundreds of millions channels). The upgraded tracker, in addition to providing improved tracking capability in a very high density environment and presenting less material, will provide a Level 1 (L1) tracking trigger that reconstructs charged particles with $P_T > 2.5$ GeV and thereby substantially improve the overall L1 trigger. A possible upgrade to the detector front-end electronics, data acquisition and high-level trigger system would allow 1-MHz first level readout and 10-kHz event storage rate. Studies are underway to ensure that precision electromagnetic calorimetry and robust jet and missing transverse energy reconstruction are maintained. A major upgrade or replacement of the end-cap and forward calorimeters is needed, as well as increased tracking coverage to extend particle flow reconstruction up to a pseudorapidity of 4. A possible electromagnetic pre-shower system, to provide pointing information for the reconstruction of $H \rightarrow \gamma\gamma$ events and excellent time-of-flight resolution for pileup mitigation is also being studied.

Science: The higher luminosity of the HL-LHC will extend the mass reach and vastly increase the sensitivity of searches for subtle signatures for new physics. Following the discovery of a Higgs boson candidate with a mass of 125 GeV, precision measurements of the properties of this new particle, in particular its mass and tree-level couplings to fermions, W and Z bosons, as well as self-coupling, will be central to the physics program. The goal is to either prove that the observed particle is the Standard Model (SM) Higgs boson or, if not, to uncover the true nature of this particle. The search for new physics beyond the SM will continue, including searches for SUSY with massive squarks and gluinos and for new heavy resonances predicted in many extensions of the SM. If SUSY is found, its relationship to Electroweak Symmetry Breaking, the hierarchy problem, and dark matter can be studied.

Collaboration: The CMS experiment is a global effort. U.S. physicists, numbering about 750 PhDs and graduate students from 50 institutions, comprise approximately 33% of CMS. The U.S. groups, supported by the DOE and the NSF, have constructed significant parts of the detector, provide a large fraction of the computing, and have led key physics analysis efforts.

Science Classification and Readiness: The science enabled by the CMS Upgrade to operate at the HL-LHC is *absolutely central.* The detector technologies required for the upgrade exist. An extensive R&D program is ongoing in order to address the remaining *significant scientific/engineering challenges to resolve before initiating construction.*

International Linear Collider: Accelerator

Description: The International Linear Collider (ILC) is a proposed high-energy, high-luminosity electron-positron colliding beam facility. It is a centerpiece in the world roadmap for particle physics. The discovery of a Higgs-like boson at the LHC motivates a strategy to build the machine to operate initially at a center-of-mass energy of about 250 GeV, followed by an increase in steps, to 350 GeV, 500 GeV and eventually to 1 TeV.

Science: The ILC will explore physics at the TeV scale, and will provide measurements complementary to those from the Large Hadron Collider (LHC), emphasizing precision measurements based on a well-controlled initial state in a low background environment. The design of the ILC and its detectors anticipated the discovery of a low-mass Higgs boson and provides an ideal instrument for measuring the full array of Higgs boson properties. These include the Higgs couplings to many fermions including charm, bottom, and top, the Higgs self-coupling, and the Higgs coupling to invisible particles such as dark matter. The ILC will add significantly to the LHC searches for new physics. The ILC has unique capabilities to discover weakly interacting particles that may be hidden in the backgrounds at the LHC. Through precision measurement of two-fermion production, W pair production, and top quark production, the ILC gives access to high mass scales, typically beyond the reach of LHC direct searches. Taken together, data from the ILC and the LHC will advance a deep understanding of electroweak unification. The ILC will thus have a major impact on our knowledge of the TeV scale and our models of higher mass scales. It will also be at the frontier of advanced technological development and international cooperation.

Collaboration: After the 2004 decision to adopt superconducting radiofrequency (SCRF) technology for the ILC, a worldwide Global Design Effort (GDE) was created by ICFA (International Committee for Future Accelerators) to advance the program. The GDE was the first fully international accelerator design effort, with partnership between Asia, Europe and the Americas. It was charged to conduct a 5-year R&D program to develop SCRF technology and achieve the gradient and yield goals; to demonstrate risk mitigating strategies; and to create a detailed conceptual design of a 500 GeV baseline machine, upgradable to 1 TeV. The design provides the basis of an international style value cost estimate, suitable for collaborative negotiations. In 2012, the GDE completed its program with successful demonstration of the 2006 goals and concluded that the technology for the project was in hand. The extensive technical design report (TDR) is presently under international review. The HEP community in Japan, with their government's concurrence, has proposed siting the ILC in Japan with a phased collision energy. This proposal aligns well with the European strategy. Details of the Japanese plan will be presented to the U.S. community in Summer 2013.

Science Classification and Readiness: The ILC accelerator enables a research program that will address questions of very great scientific importance and that is *absolutely central*. The ILC accelerator has been the subject of a comprehensive international development program with significant U.S. contributions and leadership roles. A technical design report for the accelerator facility was recently completed; the ILC accelerator is technically *ready to initiate construction* once agreements are reached in Japan and internationally.

International Linear Collider Detectors

Description: The International Linear Collider (ILC) is a proposed high-energy, high-luminosity electron-positron colliding beam facility. It is a centerpiece in the world roadmap for particle physics. The discovery of a Higgs-like boson at the LHC motivates a strategy to build the machine to operate initially at a center-of-mass energy of about 250 GeV, followed by an increase in steps, to 350 GeV, 500 GeV and eventually to 1 TeV.

Science: The ILC will explore physics at the TeV scale and will provide measurements complementary to those from the Large Hadron Collider (LHC), emphasizing precision measurements based on a well-controlled initial state in a low background environment. The design of the ILC and its detectors anticipated the discovery of a low-mass Higgs boson and provides an ideal instrument for measuring the full array of Higgs boson properties. These include the Higgs couplings to many fermions including charm, bottom, and top, the Higgs self-coupling, and the Higgs coupling to invisible particles such as dark matter. The ILC will add significantly to the LHC searches for new physics. The ILC has capabilities to discover weakly interacting particles that may be hidden in the backgrounds at the LHC. Through precision measurement of two-fermion production, W pair production, and top quark production, the ILC gives access to high mass scales, typically beyond the reach of LHC direct searches. Taken together, data from the ILC and the LHC will advance a deep understanding of electroweak unification. The ILC will thus have a major impact on our knowledge of the TeV scale and our models of higher mass scales.

Collaboration: The ILC physics program has broad international consensus. Over the last decade, extensive international detector R&D programs, in the U.S., Europe, and Japan, reached major milestones. These R&D programs have been developed largely in support of two complementary full detector designs, ILD and SiD, that will optimize the productivity of the ILC facility. A detailed baseline design report with about 1650 signatories (to date) has been written as a volume of the ILC Technical Design Report. This R&D work has also resulted in important synergistic benefits outside of particle physics, for example, detectors for experiments with X-ray free electron lasers that can provide unique research opportunities for condensed matter physics, chemistry, materials science, and structural biology. Physicists in the US have developed a well-organized effort to prepare for participation in the ILC experiments in collaboration with their international partners.

Science Classification and Readiness: The ILC detectors enable a research program that will address questions of very great scientific importance, and are classified as *absolutely central*. Detailed baseline designs for the detectors have been completed; nonetheless, engineering remains before the ILC detectors are ready to initiate construction, and for this reason the readiness classification *significant scientific/engineering challenges to resolve before initiating construction* is assigned.

Mu2e

Description: Mu2e is a facility designed to study charged lepton flavor violation in the muon sector. The experiment will exploit the Fermilab accelerator complex by redesigning the antiproton facility as a high intensity muon source. Mu2e is a major component of the Intensity Frontier program in the US and will have its physics program enhanced in the Project X era. It is an international project in the advanced design phase, with CD-1 DOE approval.

Science: Mu2e will measure the rate of coherent muon conversion to an electron in the field of a nucleus and will have a single event sensitivity of $2x10^{-16}$, which is a factor of 10,000 improvement over current experiments. The Standard Model predicts a negligible rate for charged lepton flavor violating processes, while many models for new physics predict rates accessible at Mu2e. Mu2e will be sensitive to new physics effects well above the TeV scale and that are beyond the direct reach of the LHC or a future lepton collider. Charged lepton flavor violating processes are influenced by the mechanism responsible for neutrino mass generation, and so Mu2e can play a key role in uncovering the origin of neutrino masses.

The MEG experiment at PSI in Switzerland is searching for the related process $\mu^+ \rightarrow e^+ \gamma$, which is sensitive to new physics that appears in loops with an emitted photon. The Mu2e experiment is significantly more sensitive to the existence of lepton flavor violation than is the MEG experiment, however. The combination of MEG and Mu2e is a powerful discriminator between new physics models, and the experiments are complementary. The proposed COMET experiment at JPARC is potentially competition to Mu2e, although only the first phase of COMET, reaching a sensitivity of about 3×10^{-15}, is currently approved.

Collaboration: The Mu2e collaboration has 140 physicists from 26 institutions, including 5 institutions from Italy and 2 from Russia and the collaboration continues to grow. The DOE funds the majority of the project, although discussions with INFN regarding the funding of a significant fraction of the calorimeter are at an advanced state.

Science Classification and Readiness: The search for charged lepton flavor violation is a problem of very great scientific importance. The Mu2e experiment will improve the limits on flavor violation in muon interactions by four orders of magnitude and reach a sensitivity at which a positive signal would be expected in many models. The Mu2e experiment is *absolutely central* to world-leading science. The 2008 P5 report strongly recommended pursuing Mu2e in all budget scenarios considered by the panel. The project has CD-1 approval and is in the advanced engineering design phase; therefore, it is classified as *ready to initiate construction*.

LBNE

Description: The Long Baseline Neutrino Experiment (LBNE) will construct an intense neutrino beam from the Fermilab accelerator complex to a massive neutrino detector located at a distance of 1300 km at the Homestake mine in South Dakota. The beam will provide a broad range of neutrino energies. It will initially be operated at 700 kW and will be capable of operations at 2.3 MW following construction of Project X. The detector will be a large liquid argon time projection chamber. This detector, capable of millimeter track resolution and initially 10 kilotons in mass, will be a major advance in neutrino detection technology. The detector is planned to be constructed on the surface in this initial phase; however, later phases with larger detectors underground are envisioned. Once located underground, the detector will also be capable of search for proton decay and of detection of neutrinos from galactic supernovae.

Science: The discovery of neutrino mass and oscillations is the first laboratory signal for physics beyond the Standard Model and introduces a new source of charge-parity (CP) violation that could help explain the matter-antimatter asymmetry of the Universe. The LBNE experiment will study the phenomenon of neutrino oscillations using beams of both neutrinos and antineutrinos at long baseline over a broad range of neutrino energies. The experiment's long baseline is crucial for resolving potential ambiguities among the parameters of neutrino oscillation, in particular the CP phase δ and the neutrino mass hierarchy. In its first stage, LBNE will resolve the neutrino mass hierarchy at $>3\sigma$ C.L. for 75% of the allowed values of δ (100% if results from other experiments are included), and can establish CP violation at 99% C.L. for >50% of the allowed values of δ. It would establish a world-leading program for more precise and possibly decisive future measurements. Additionally, the combination of long baseline and broadband beam will enable LBNE to characterize the oscillation probabilities for neutrinos and antineutrinos over a wide range of energies enabling sensitive searches in later stages for non-standard effects that would result from physics beyond the Standard Model.

Collaboration: The LBNE science collaboration currently consists of 360 scientists from 70 institutions drawn mostly from the United States, but also India, Italy, Japan, and the United Kingdom. The collaboration is growing and is likely to be substantially larger as the project progresses. Significant participation and contributions from international collaborators could considerably enlarge the science program of the first stage of LBNE by enabling construction of a near detector, increased mass of the far detector, and relocation of the far detector underground.

Science Classification and Readiness: With its combination of a broadband and high-intensity neutrino beam, long baseline, and sensitive detector, LBNE will establish a world-leading program using neutrinos to search for the origin of the matter-antimatter asymmetry in the Universe and physics beyond the Standard Model. The ability of the first stage of LBNE to contribute world-leading science is classified as *important*, and it lays the foundations for an *absolutely central* world-class neutrino program as a core component of the US HEP program, as called for by the 2008 P5 report. The project has CD-1 approval and is therefore classified as *ready to initiate construction*.

PROJECT X

Description: Project X is a high-intensity proton facility that will support an intensity frontier physics program at Fermilab. It is foreseen to be built in three stages. Stage 1 is a superconducting 1-MW 1-GeV continuous wave (cw) linac, and also includes a spallation target optimized for particle physics. The aging existing linac is replaced in Stage 1, and the aging existing Booster is replaced in a subsequent stage. The changes made in Stage 1 and the subsequent stages result in a unique facility with a cw superconducting linac that can deliver up to 1 MW and 3 MW of beam power at 1 and 3 GeV, respectively. In addition a pulsed linac provides 350 KW of power at 8 GeV to drive an 8-GeV research program and the existing Recycler/Main Injector complex. Upgrades to this complex increase by a factor of 3 the beam power at 60 GeV to 120 GeV.

Science: The suite of intensity frontier experiments that are either made possible or are improved by Project X is very broad, and individual experiments run the spectrum from *important* to *absolutely central*. Stage 1 makes electric dipole moment and neutron anti-neutron oscillation experiments possible, increases the power by a factor of 10 to the muon experiments (e.g. Mu2e, g-2, …). In addition Stage 1 makes it possible to use different targets for the Mu2e experiment, which could play an important role in determining the physics responsible for the decay if a discovery is made. It more than doubles the power to the rare kaon decay experiment (ORKA), triples the 8-GeV power available to future short baseline neutrino experiments, increases the power available to the long baseline neutrino program (LBNE) by a factor of 1.7. Subsequent stages further increase the power available to these experiments, and hence their reach. The power to the short baseline neutrino program increases by a further factor of 4 in Stage 3. Stage 2 increases the power available to the rare kaon decay experiments by a further factor of 10 making a unique and detailed study of the CP violating decay $K_L \to \pi^0 \nu \bar{\nu}$ possible. The subsequent stages of Project X increase the power available to LBNE ultimately reaching 2.3MW in Stage 3 . The electric dipole and neutron anti-neutron experiments require in addition a spallation target, which enables a program of muon spin rotation experiments for materials science and provides a high-energy neutron irradiation source. This neutron source could enable material developments and testing important for nuclear energy and fusion science applications.

Collaboration: Project X accelerator R&D has been undertaken as a collaboration of twelve national laboratories and universities as well as four Indian laboratories. The Project X research program is of interest to the international particle and nuclear physics communities. It could also be of interest to the materials sciences, fusion energy sciences, and nuclear energy sciences communities. Muon spin rotation applications and irradiation facility applications were explored in two recent workshops.

Science Classification and Readiness: The importance and breadth of the research program that the Project X accelerator facility enables and enhances leads the accelerator facility to be classified as *absolutely central*. Although R&D is still required for the spallation target needed by some experiments, all stages of the Project X accelerator facility are *ready to initiate construction.* Project X experiments that compose the research program range from important to absolutely central, but scientifically the Project X research program as a whole is classified as *absolutely central*. Being in the planning phase, the construction readiness of the Project X research program is classified as *mission and technical requirements not yet fully defined*, although some experiments are beyond this phase.

nuSTORM

Description: NuSTORM would be a muon storage ring at Fermilab that would produce well-understood neutrino beams suitable for short baseline studies, including determinations of eV-scale neutrino oscillation parameters and neutrino cross sections. To produce the beams, pions generated by protons on a conventional target would be collected and injected into a racetrack-shaped storage ring, where muons from their decay would be captured and briefly stored. The decay $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$, with muon momenta near 4 GeV, would then produce a neutrino beam with a well-understood composition and spectrum. NuSTORM would make use of some of the concepts of a neutrino factory, and would serve as a test-bed for key technologies such as 4D muon cooling. While the concept for nuSTORM is not new, the nuSTORM design is in the early stages of development.

Science: NuSTORM, together with suitable detectors, would explore large-Δm^2 phenomena. For example, with a 1.3kT magnetized iron far detector and an exposure of 10^{21} protons on target (~5 years of running), nuSTORM could measure ν_e to ν_μ appearance with 10σ statistical significance for the parameters of the LSND observation. With an appropriate near detector, it could study anti-ν_μ or ν_e disappearance. The confirmation of oscillations beyond those of the standard three-flavor neutrino model (PMNS) would be an extraordinary discovery, and would motivate an extensive program to measure precisely the oscillation parameters. NuSTORM's well-characterized neutrino beams could offer a unique facility for this purpose. It could also precisely determine anti-ν_μ and ν_e cross sections that will otherwise be an important source of systematic uncertainty for future long-baseline experiments.

Context: Various approaches are being explored to look for $\nu_\mu \rightarrow \nu_e$ appearance or anti-ν_e disappearance. Some studies have shown that the desired sensitivity could be reached by placing an intense source of neutrinos near or inside an existing detector such as SNO+, KamLAND, Borexino, Daya Bay or gadolinium-doped SuperK. Radioactive sources have been considered, as well as others using collision-activated isotopes or neutrinos from stopped kaons or pions. Alternatively, a conventional source combined with very large liquid argon time projection chambers, possibly coupled with muon spectrometers for ν_μ identification, could probe sterile neutrino hypotheses. Neither of these provides the well-characterized neutrino beams offered by nuSTORM.

Collaboration: The nuSTORM Collaboration submitted a Letter of Intent to the Fermilab PAC in June 2012, and a full proposal is planned for June 2013. Their July submission to the update of the European Strategy had 66 signatories from 19 institutions in the U.S., Europe and Japan, including a large contingent from the UK.

Science Classification and Readiness: Sterile neutrinos would violate a basic tenet of the Standard Model, the three-generation structure of the leptons, and if confirmed, full exploration would be essential. NuSTORM would be a superb facility for such a program. Nonetheless, nuSTORM is still in the early stages of planning; consequently, until a design is available and an anomaly has been convincingly demonstrated, we *don't know enough yet* to assess nuSTORM's ability to contribute to world-leading science. While the subpanel is not aware of major technical challenges facing nuSTORM, it is unable to evaluate construction readiness based on the currently available information and classify nuSTORM as *mission and technical requirements are not yet fully defined*.

Generation 3 Direct Detection Dark Matter Experiments

Description: The 2009 PASAG (Particle Astrophysics Scientific Advisory Group) report defined "Generation 3" (G3) direct detection searches for Weakly Interacting Massive Particles (WIMPs) as reaching at least 10^{-47} cm^2/nucleon (spin independent cross section typically in the 50 to 100 GeV/c^2 mass region). Given the evolution of the theoretical and experimental landscape, the class of experiments proposed here is more generally described as a follow-up to the "Generation 2" (G2) experiments either currently being built (Xenon 1 ton, DEAP3600, XMASS 1 ton) or in advanced R&D for selection by DOE and NSF in the coming year. The results of the G2 experiments should be available in the 2017–2020 time frame. Depending on the nature of the G2 results, G3 experiments will either need to continue the search or, if a signal has been observed, collect statistics. The focus of G3 experiments will depend on the experimental evidence gathered in the coming five years and possible shifts of paradigm. This may require significant adaptation on the technologies used. Either in the statistics-building mode or in the search mode, it is important for the experiments to operate with negligible background. At least two different targets would be highly desirable to decrease the scientific and technical risk in search mode and provide cross checks on results in large statistics mode.

Science: The nature of the ubiquitous dark matter in the universe is a central problem of cosmology and the possibility that it is made of particles produced in the early universe remains an attractive concept, which would further unite the physics at small and large scale. Apart from axions or sterile neutrinos, not considered here, two classes of models are currently intensely studied: i) the WIMP proper whose existence and density are explained by new physics at the weak scale (e.g., supersymmetry); ii) a dark sector either with symmetric or asymmetric dark matter, which could self-interact through a light mediator and exhibit a complex structure. For a dark particle-antiparticle asymmetry similar to that of the baryons, a mass in the few GeV/c^2 would be favored. Both types of models also have implications for the LHC and indirect experiments. More generally, the three approaches are complementary. In particular, direct (and indirect) detection experiments may be able to bring additional information on signals that could be observed at the LHC (e.g., help break ambiguities). If no new physics is observed at the LHC, direct and indirect particle dark matter detection could help pin down the scale for new physics, since, contrary to colliders, the astrophysics searches are not restricted by sharp production thresholds.

Collaboration: The G2 down-selection is likely to lead to a substantial reorganization of the existing collaborations. In order to maintain its current leadership, the U.S. dark matter community will likely propose to have a leading role in at least two international G3 collaborations.

Science Classification and Readiness: The G3 Direct Detection Dark Matter program is *absolutely central*. This third generation of detectors requires *significant scientific/engineering challenges to resolve before initiating construction*. The G2 experiments will likely provide the demonstration of the basic technologies to be used for the G3 program. Additional R&D will be needed to optimize the sensitivity and threshold of the detectors.

LSST

Description: The Large Synoptic Survey Telescope is an 8.4-meter (6.8-meter effective aperture) telescope with a wide, 3.5-degree field of view and a 3-Gigapixel CCD camera under construction at Cerro Pachon in Chile. Over 10 years starting early in the 2020 decade, LSST will carry out deep, wide, fast, multi-band, time-domain optical imaging surveys of the southern sky and make derived data products available on a rapid timescale. LSST is a partnership between the NSF and the DOE, with additional support from private sources, including participating institutions. LSST is the major next-generation component in the DOE's program to understand the nature of the Dark Energy that constitutes 70% of the Universe and to explore the physical origin of the accelerating expansion of the Universe. It will also make possible a very broad array of new studies in astronomy, ranging from an inventory of small bodies in the solar system to the formation and evolution of galaxies. It is anticipated to be potentially transformative in opening up new windows in the study of astrophysical transient phenomena.

Science: The LSST will map and measure the properties of several billion galaxies over nearly half the sky and discover tens of thousands of distant supernovae. These data will be used to probe dark energy via weak and strong gravitational lensing, the large-scale distribution of galaxies (including baryon acoustic oscillations), the abundance of massive clusters of galaxies, and supernova distance measurements. LSST is expected to reach a factor of 5-10 improvement in the Dark Energy Task Force Figure of Merit compared to currently operating experiments. The scientific questions that LSST will address, namely (1) whether dark energy or a modification of gravity is the source of cosmic acceleration and (2) detailed studies of the nature of dark energy, are of primary scientific significance, and the ability of LSST to resolve these science questions is substantial. The other astrophysical measurements LSST will enable are of high priority to the astronomy community, as reflected, e.g., in LSST ranking as the top, large ground-based project by the Astro2010 decadal survey. In this broader mission, LSST will serve a very large and diverse astronomy community and is seen as the centerpiece of the U.S. optical/near-infrared system in the next decade.

The combination of large telescope aperture, wide field of view, and sensitive detectors will make LSST a uniquely powerful, world-leading facility for carrying out wide, deep, fast imaging surveys for dark energy and other astronomical studies. It will measure roughly an order of magnitude more galaxies and supernovae than any currently operating optical astronomy facilities; no other facility of this capability is under consideration around the world. The ESA Euclid space mission will use a smaller-aperture telescope with optical and near-infrared imagers and multi-object spectrographs to carry out surveys for dark energy. It is not expected to include a substantial time domain survey. NASA is considering options for WFIRST, the top-ranked, large space mission in Astro2010, which would carry out deep, near-infrared imaging and spectroscopic surveys with a variety of science goals, including dark energy. These space missions would complement the science reach and capabilities of LSST.

Collaboration: The LSST is a joint DOE/NSF project. The data set obtained for dark energy studies can also address a wide array of astrophysics problems, ranging from an inventory of small bodies in the solar system to the formation and evolution of galaxies. The most recent NRC decadal survey for astronomy and astrophysics gave the LSST its top ranking for a new ground-based project because of "its compelling science case and capacity to address so many of the science goals of this [decadal] survey and its readiness for submission to the MREFC process [at NSF]." An MOU between DOE and NSF has defined each agency's responsibility for the project during construction and operations.

Science Classification and Readiness: The ability of LSST to contribute to world-leading science is *absolutely central*. The LSST telescope project has been approved by the National Science Board for MREFC funding at NSF, and the LSST camera project has been awarded CD-1 approval by DOE. LSST is therefore classified as *ready to initiate construction*.

Next Generation Dark Energy Experiment

Description: The US has a well-defined program of world-leading dark energy experiments at the Cosmic Frontier, progressing from BOSS and DES (near term) to MS-DESI (intermediate term) to LSST (operating in the 2020 decade). DES and LSST are ground-based imaging surveys, while BOSS and MS-DESI are ground-based spectroscopic redshift surveys. These projects are expected to achieve constraints on dark energy properties at the level of Stage III (for DES and BOSS) and Stage IV (for MS-DESI and LSST) projects as defined by the HEPAP/AAAC Dark Energy Task Force committee. To fully implement a coherent dark energy program, however, an experiment that can reach a precision beyond that of MS-DESI and that would complement LSST could be necessary. P5 and the Astro2010 Decadal Survey recommended at high priority DOE participation in partnership with NASA in a space-based mission, now called WFIRST, which would have the study of dark energy as one of its primary goals. Concepts for other dark energy experiments complementary to LSST, e.g., deep surveys using new optical or radio telescopes, are also being explored. The Snowmass process and the first results from DES (and further results from BOSS) will help shape the future contours of this field.

Science: Observations over the last decade, building upon the supernova discoveries announced in 1998, have provided firm evidence that the expansion of the Universe is speeding up. Although constraints upon the properties of dark energy have improved in the intervening years, we still cannot answer the fundamental question of why the expansion is accelerating nor determine with high precision the nature of the dark energy that makes up 70% of the Universe. The scientific questions that a Next Generation Dark Energy experiment would address, namely (1) whether dark energy or a modification of gravity is the source of cosmic acceleration and (2) detailed studies of the nature of dark energy, are of primary scientific significance, and the ability of the next generation experiment to resolve these questions will be substantial. It is likely that such an experiment would enable other astrophysical measurements that are will be of considerable interest to the astronomy community.

Collaboration: Dark Energy research has attracted a growing segment of the HEP community, and the U.S. retains a strong leadership role in this subfield. This provides a strong basis for forming a successful collaboration whichever experimental approach is selected. Funding will likely come from DOE in partnership with either NASA (for a space mission) or NSF (which operates ground-based facilities).

Science Classification and Readiness: A next-generation dark energy facility would be world-leading and, given the importance of the fundamental questions that it would address (such as the nature of 70% of the universe), it is *absolutely central*. The readiness of the facility depends upon which facility concept is pursued; consequently, the construction readiness of the next generation dark energy experiment is classified as *mission and technical requirements are not yet fully defined*.