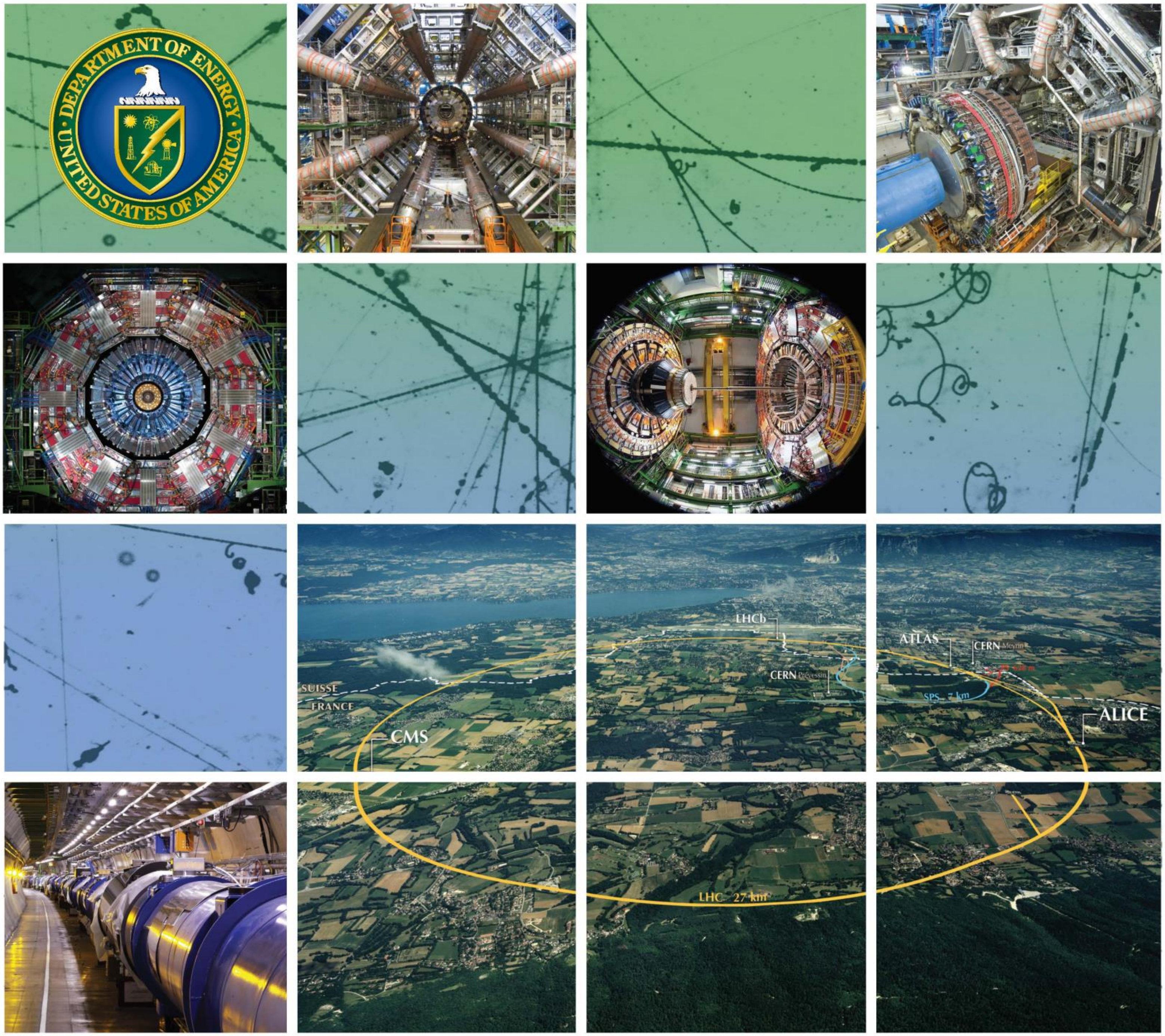

Office of Science

High Energy Physics Portfolio Review:

Report of the Large Hadron Collider Subpanel

Executive Summary

The most prominent experimental particle physics program in the world currently is that at the CERN Large Hadron Collider. Collider experiments probe the fundamental laws of nature at the highest energy scales, or the shortest distances. Experiments at the LHC have led us to explore the microscopic world at scales less than 10^{-18} meters. The U.S. Department of Energy supported programs have contributed to the construction of the collider itself and to the two general-purpose detectors, ATLAS and CMS. In each experiment, the strength of the support for the Operations and Research Programs surpasses that of any single country. An important component of the contributions is the intellectual talent provided by faculty, scientists, technical and professional staff, postdoctoral appointees, graduate students and undergraduates. Together, there are approximately 1,000 United States authors on the scientific publications from the two experiments. Significant U.S. intellectual, technical, and resource contributions ensure that the United States continues to play a world-leading role in this important program of physics, even as the facility is located offshore. The program was featured as a high priority in the Particle Physics Project Prioritization Panel Report of 2014. The schedule of the LHC, including the experimental program, is summarized in Figure 1.

The subpanel found that the scientists of the U.S. DOE programs in ATLAS and CMS pay considerable attention to understanding the resources needed to match their prorated contributions to the construction, operations, and computing for the experiments. In general, the program contributes at, or, in the case of computing, slightly above the pledges within the international collaborations. The resources needed to maintain this level are broadly justified. The emphases in the Physics Research programs of the two groups map well on to those aspects of the program highly recommended by the High Energy Physics Advisory Panel.

Nevertheless, the scale of resources involved is large. The experiments should feel motivated to continue to seek synergies that can be exploited to reduce effort across the program and with other physics and scientific fields.

Thirty years ago, the recognition of the peculiar, event structured, data in particle physics, permitted the use of multiple modest, even commodity, computers in large numbers at significantly lower cost than mainframes. The scale of the future needs for Run 3 of the LHC and particularly for the high luminosity phase, HL-LHC, probably demands an analogous change of approach. What is recognized is the need to use diverse and heterogeneous architectures and to exploit high performance computing facilities, cloud services and data center facilities. The experiments should not underestimate the effort needed to ensure success in this new environment. A paradigm shift in the manner in which the analyses are performed, to enhance the productivity of the experiments, could perhaps be envisaged.

The breadth of opportunities that are available to junior scientists in high technology detectors, computing, machine learning, collaborative endeavors, and scientific discovery, is impressive. It is important that the collaborations prioritize the training and mentoring of junior scientists.

Increased efforts in enhancing the diversity and inclusion of this experience could ensure not only benefits for society but also the attraction of the brightest and best to enter the field. The potential for the junior scientists who participate in this DOE program to influence society is amplified by them enjoying a good experience as students and postdoctoral fellows.

The overall performance of the programs covering the challenging experimentation, the large-scale management, and most importantly, the physics outcome is excellent. The stage is set for a world-leading program during the next two decades.

1. Introduction

The Energy Frontier program is managed within the Office of High Energy Physics in the Office of Science of the United States Department of Energy (DOE). This program, along with the National Science Foundation (NSF), supports the participation of United States groups from Office of Science National Laboratories and from Universities, in the two large, general-purpose detectors, ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid), operating at the Large Hadron Collider (LHC) at CERN on the Swiss-French border near Geneva, Switzerland. The schedule of the LHC, is summarized in Figure 1. This report will, except where indicated otherwise, focus on the DOE-supported activities, but for economy we may use the terms U.S. ATLAS and U.S. CMS.

Relative to the U.S. particle physics program these two experiments represent a sizable fraction of the annual budget. Indeed the DOE component alone is larger, in each experiment, than the contribution from any other single country. In this report, we examine the success of the DOE component of the program, and then examine the impact of the DOE roles on the resulting physics output, and the experiments more generally.

The report in 2014 of P5, the Particle Physics Project Prioritization Panel[1], is the source of the strategic plan for high energy physics in the United States. It is consistent with other plans such as the 2013 Update of the European Strategy for Particle Physics[2]. With time, conditions change, and budgets do not necessarily evolve as posited in the working assumptions of the P5

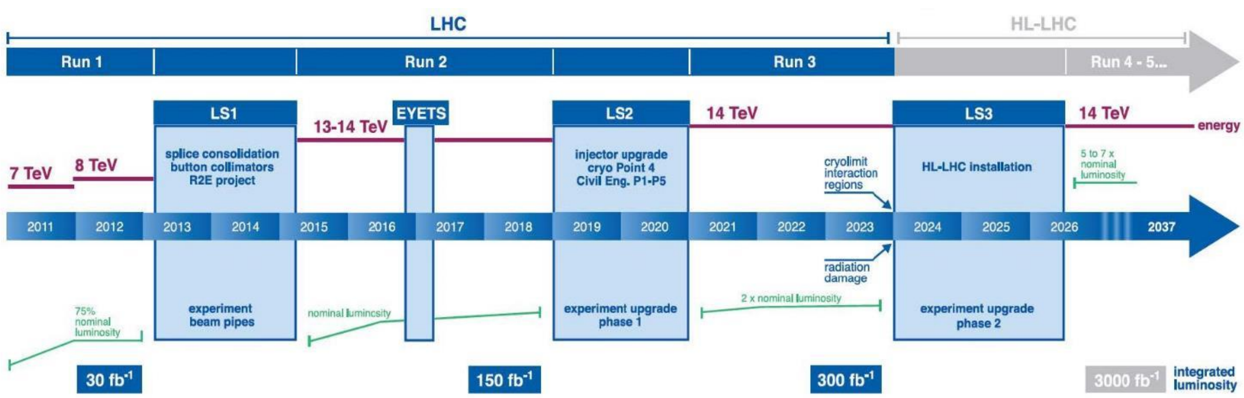

Figure 1: Operations, Upgrade, and Installation schedule for the Large Hadron Collider and the LHC Experiments, including the planned timeline for long shutdowns of the LHC, the center-of-mass energy and integrated luminosity during past and anticipated future physics runs. The nominal luminosity is the LHC design at 1 x 10^{34} $cm^{-2}s^{-1}$. Dates indicate calendar year.

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[1] "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context", the report of the Particle Physics Project Prioritization Panel (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP), was approved by HEPAP on May 22, 2014 and is available online at: https://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf.

[2] "The European Strategy for Particle Physics Update 2013" was formally adopted by the CERN Council at its Session of March 22, 2013 and is available online at: https://cds.cern.ch/record/1567258/files/esc-e-106.pdf.

deliberations. A number of bodies such as the 2016 DOE-HEP Committee of Visitors[3] recommended ensuring a strategic plan consistent with P5 but taking account of future operations demands. In October 2017, the Office of Science tasked the High Energy Physics Advisory Panel (HEPAP) with conducting a "portfolio review" of the DOE-HEP program. A copy of the charge letter constitutes Appendix A of this report. In conjunction with DOE-HEP, HEPAP created two subpanels, one to consider the general purpose LHC experiments, ATLAS and CMS, and one to consider thirteen other experiments within the Intensity and Cosmic Frontiers to which the charge also applied.

The LHC Subpanel was formed in January 2018. The proponents of the LHC experiments, upon receiving the charge letter and additional details on proposal preparation from the DOE in November 2017, responded to their instructions by submitting extensive reference material by the beginning of February 2018. The subpanel met for the first time in Rockville, Maryland on February 26-27, 2018. The sessions on the first day were occupied by interactions with the proponents, presentations, and subpanel deliberations. Following an executive session with DOE-HEP, the morning was devoted to ATLAS. The afternoon was devoted to CMS followed by a second executive session in which initial discussions were engaged. The morning of the second day was used for further discussions, and to develop the narratives for each experiment. The afternoon session was spent to reach a broad consensus on the thrust of the report and to begin drafting it.

During the subsequent three weeks, the report was refined and a final meeting of the subpanel was held on March 26, 2018, in Rockville, Maryland. Together the subpanel read, considered, and completed the draft report. Representatives of the DOE Office of HEP were present during the deliberations.

Following this Introduction, Section 2, Program, of the subpanel's report contains the three subsections in which attention is paid to findings, which are important factual statements, and comments for the LHC experiments. The comments, which are emphasized with bold face type, transmit the reactions and sentiments of the subpanel. Some items, common to ATLAS and CMS, were identified for inclusion in the third subsection termed Program-Wide Considerations. Section 3 of the report contains a brief set of Conclusions.

While the LHC subpanel acknowledges the important contributions of the NSF-supported participants in the U.S. LHC program, this report does not explicitly discuss those activities. The subpanel was charged with evaluating the DOE-supported component of the United States programs in the international experiments, ATLAS and CMS. Where specific reference to the DOE component was needed for clarity, these have been included. However, on occasion, the

[3] The 2016 report of the DOE High Energy Physics Committee of Visitors was presented to the High Energy Physics Advisory Panel (HEPAP) at the HEPAP meeting of December 1-2, 2016. The report, approved by HEPAP, is available online at: https://science.energy.gov/~/media/sc-2/pdf/cov-hep/2016/HEP_COV_2016_Report.pdf.

committee found it more appropriate to simply refer to U.S. ATLAS or U.S. CMS, in the expectation that this will not lead to any confusion.

As well as the charge letter, the appendices contain the membership of the subpanel, the dates and agendas of the two panel meetings, and a glossary of acronyms used in the report.

2. Program

a. ATLAS Experiment

The ATLAS experiment has been assessed over the period FY 2019 to FY 2022, with attention paid to the scientific output, contribution to operation that preserves the data acquisition and quality, and contributions to technical upgrades. ATLAS is one of the two large general-purpose detectors operating at the LHC, of unprecedented size and complexity. It is currently completing a data taking phase in a configuration that is well understood, with an operation methodology, calibration, and analysis model that is in a quite mature stage. A total data set of more than 150 fb^{-1} is anticipated to be collected before the end of LHC Run 2. The experiment's most ambitious physics goals require higher sensitivity that may be met only in the HL-LHC running period. The ATLAS detector will be upgraded during the upcoming LHC long shutdown in 2019-2020, and the experiment plans to record an additional 150 fb^{-1}, or possibly more in Run 3 from 2021-2023. The higher luminosity comes with a much more challenging event environment, in particular the increasing pile-up that will reach on-average 200 interactions per crossing at HL-LHC. Thus, significant detector and computing infrastructure upgrades are essential to operate in this environment with efficiency comparable to the current running conditions. This major upgrade, to be installed and commissioned in the period 2024-2026, will enable the experiment to operate in the high luminosity phase of the LHC collider, aiming to record a data set of up to 4,000 fb^{-1}**.** The U.S. ATLAS team represents about 20% of the ATLAS collaboration and is supported by DOE and NSF. The team supported by DOE comprises 4 national laboratories, ANL, BNL (U.S. DOE host laboratory for ATLAS), LBNL, SLAC and 31 universities. In addition, NSF supports the contribution of 10 universities. Currently several physics Working Group leadership positions are held by U.S. ATLAS physicists as are numerous sub-group convenorships. At the time of this review, a physicist from the U.S. is the ATLAS Computing Coordinator, and another, responsible for the Upgrades, is a member of the ATLAS Management Team. **The U.S. ATLAS collaboration contributes to the analysis effort, detector maintenance and operations, computing, and detector upgrades, demonstrating leadership in all these components.**

The ATLAS experiment is pursuing a broad and comprehensive program of physics studies, including measurements of the properties of the Higgs boson, precision tests of the Standard Model, and searches for dark matter and evidence of physics beyond the Standard Model, both with direct evidence for new particles as well as indirect evidence of new physics through precision measurements of processes suppressed in the Standard Model. In the period between 2019 and 2022, the U.S. ATLAS collaboration is focusing on five major science research goals: operations, technology for the upgrades, and three key analysis streams, namely Higgs physics, indirect probes of new physics, and searches for signatures beyond the Standard Model. **The U.S. ATLAS objectives and planning are aligned with the P5 priorities and the science drivers that map onto the Energy Frontier program in particle physics.**

The ATLAS experiment operates and records proton-proton collisions at the highest energies currently available. Increasing luminosities lead to severe backgrounds, radiation damage and pile-up that represent unprecedented challenges. The physics results, including the investigation of the properties of the Higgs boson and the outcome of the searches for new physics signatures, are vital to the direction of the entire field of particle physics. As recognized by P5, the scientific merit of this program is amongst the highest in the field. The physics opportunities have been exploited with a solid body of publications: at the time of this review, the collaboration has published more than 700 papers in a broad range of topics; 55 papers, using the full 2015-2016 data set, have been submitted for publication. The Higgs discovery was a crucial milestone in particle physics, and the study of its couplings is important to confirming that it behaves as predicted within the Standard Model. Precision measurements of these couplings in the next phases of the experiment at higher luminosity would serve as powerful probes for new physics effects. The search for new particles not predicted by the Standard Model may have a deep connection with the elucidation of the nature of dark matter. Other searches for exotic particles are closely connected to the effort of identifying the nature of the physics beyond the Standard Model and have connections with other precision studies, including those that are pursued at Intensity Frontier physics experiments such as Belle II and LHCb. **The U.S. ATLAS teams have a strong presence in physics analysis, investing their efforts judiciously in topics such as Higgs physics, exotica, dark matter, and hidden sectors. Overall the ATLAS experiment is well-poised to record collision data in the next phase of the program and extract physics results in a broad range of physics areas.**

At the end of the 2017 run, the LHC exceeded its design instantaneous luminosity; ATLAS succeeded in operating the detector in an environment with higher backgrounds and higher pile-up than initially foreseen. The ATLAS detector is now in a mature state, with its performance calibrated and continuing to improve. The collaboration has also developed and deployed powerful techniques for data handling and data analysis, which will be instrumental in improving and broadening its physics reach with future datasets. However, the experiment will face new challenges during the higher luminosity operations of LHC, which involve much higher event pile-up. The initial Phase-I and High-Luminosity (HL)-LHC (Phase-II) ATLAS detector upgrades have been designed to enable the experiment to operate, record and reconstruct LHC collision events under these conditions and are critical to achieving the desired physics goals. The U.S. ATLAS team has been crucial to the implementation of the design and construction of the ATLAS detector that is currently taking data. They are engaged in the fabrication of components to be installed in the Phase-I upgrade, expected to start its data taking phase in 2021, with areas of participation including the muon New Small Wheel (NSW) and trigger and data acquisition upgrades. The panel notes that the muon NSW has had some recent difficulties and its schedule is at risk; this is being addressed by a collaboration-wide effort. Finally, the U.S. ATLAS team is planning on contributing to key components of the HL-LHC detector upgrade, in particular the inner tracking system, the Liquid Argon and Tile calorimeters, and the muon system, including various electronics components for these subsystems and the corresponding data acquisition elements. **The development, operation and physics exploitation of ATLAS has been instrumental in advancing new detector technologies, state of the art radiation-hard**

electronics, large-scale computing techniques, and data analysis methods, including machine learning; these have influenced the whole field. Exploiting these advances, the U.S. ATLAS collaboration provides key contributions to the operation of the current detector as well as to its planned upgrades, utilizing technical infrastructure available at the four DOE National Laboratory partners and universities equipped with technical capabilities.

ATLAS analyses are performed by teams of scientists: U.S. ATLAS tracks the associated expenditure of U.S. resources through polls of DOE-funded institutes and consistency checks with operations and project databases. Workload estimates, based on a fine-grained accounting of the analysis workflow, are parsed into collaboration-wide vs. analysis-specific efforts. The workload per paper varies but is estimated to average around 5 Full-Time Equivalent (FTE) effort among 15 authors across the current total of ATLAS papers during the typical peak analysis year of a result. The analyses are carefully checked by assigned review committees, the working groups, the entire international collaboration, the Publication Committee Chair, and the Spokesman (or delegate), before results are submitted to a scientific journal. **The path for an analysis from idea to publication is long and complex. Such a high level of effort may be required for highly complex and high priority studies, but a mature experiment like ATLAS could also be expected to facilitate creative and less complicated analyses that are doable in less time and by significantly smaller teams. Such an approach could broaden the experience, skills, and physics perspectives of the participating students and postdocs.**

One of the key aspects of the experiments, which was reviewed is the effectiveness of the training of young Science, Technology, Engineering, and Mathematics (STEM) professionals, an important area of national interest. The U.S. ATLAS scientific authors include, at the time of this review, 246 PhD students, and, to date, 347 U.S. students have obtained their PhD from ATLAS. In addition, postdoctoral research associates contribute to physics analysis and operation tasks. **Mentoring and advising of early career scientists is an important responsibility of the collaboration. Evidence for significant methodical or organized professional development of young scientists, which could be considered as a role for the ATLAS Centers (ATCs), was not presented. In order to assess mentoring success, U.S. ATLAS is encouraged also to make efforts in longitudinal tracking of postdoctoral research associates and accumulate statistics on the fractions pursuing careers in academia, laboratories, industry, and other sectors**.

The effort required for operations, physics analysis, and upgrade work does not vary during the funding period considered. The division of efforts is expected to be the same across two different periods, namely a long shutdown of LHC to install Phase-I upgrades and the early data taking of Run 3. The DOE universities approximately deploy 22% of their effort in operations, 47% in physics analysis work, and 31% in upgrade work. The corresponding balance of activities in DOE laboratories is 34%, 26%, and 40%. For FY 2019, U.S. ATLAS expects about 150 FTEs from laboratories and 343 FTEs from DOE-supported universities across the Research, Operations, and Project areas of the program. The DOE-supported laboratory effort in FY 2019 includes approximately 20 FTE (administrative staff), 61 FTE (engineering and professional support), 39

FTE (senior scientists), and 21 FTE (postdoctoral associates). The DOE-supported university effort in FY 2019 includes approximately 78 FTE (faculty), 53 FTE (engineering and professional support), 68 FTE (postdoctoral associates), 110 FTE (graduate students) and 10 FTE (undergraduate students). The U.S. ATLAS team considers the current size of the program adequate to carry out the HL-LHC program. Four DOE national laboratories participate in the U.S. ATLAS program. Each laboratory is responsible for a different aspect of operations and the HL-LHC upgrade project and supports an ATLAS Center. The ATCs have hosted approximately 50 graduate students in four years and organized ATLAS and U.S. ATLAS topical workshops. In the past four years, members of U.S. ATLAS held approximately 80 of the 440 high-level appointments in the collaboration. Finally, in the past four years, U.S. ATLAS speakers gave 114 of the approximately 500 talks at major conferences. The strengths of the U.S. ATLAS group exploited in the experiments range from the development of new analysis techniques, such as the jet substructure studies, to computing expertise, to technology strengths such as the expertise in silicon detector construction and Field-Programmable Gate Array (FPGA) algorithm development. **On average, the DOE-supported university balance of activities is consistent with the stated priorities, and the contributions to operations are important. There is some concern that the educational mission of the four ATCs is not clearly articulated and that the impact on the mentoring of junior scientists could be enhanced. U.S. ATLAS should consider re-evaluating the current ATC implementation.**

Data processing is an integral component of an efficient physics analysis throughput. The Brookhaven National Laboratory Tier-1 center and NSF-supported university Tier-2 computing centers are an integral part of the ATLAS computing infrastructure. The anticipated data set is two times larger for the next run and will be an order of magnitude larger in the HL-LHC era. The current computing model will be pushed to its limit for the upcoming run and potentially fail for HL-LHC. The DOE-supported ATLAS group has effectively used the Advanced Scientific Computing Research (ASCR) supercomputing resources at ANL, LBNL, and ORNL for a number of tasks. The ultimate aim of such work would be a complete workflow that can handle event generation, detector simulation, event reconstruction, and analysis. A number of optimizations and the (somewhat belated) introduction of multithreading has enabled the use of modern multi-core processing beyond the single-core per job model. While this is a move in the right direction, much more work will be needed — across multiple levels of code organization — to satisfactorily address the problem of dealing with next-generation systems. **It is important that additional effort be directed towards a new computing model, including a cost model for funding agencies, which ensures data processing and efficient analysis throughput in the HL-LHC running period. In particular, newly emerging computer architectures should be studied and their impact on the performance of the existing code base should be evaluated. Additional burdens for the funding agencies should be identified early and carefully assessed**.

The U.S. LHC research program funding by DOE-HEP has already diminished during the past five years. This has led to a reduction in the number of physicists and students in ATLAS. The U.S. LHC operations program funded by DOE-HEP has also suffered a reduction over these years. In response to a request from DOE for a prioritized list for the research and operations programs to prepare for possible further reductions in support, U.S. ATLAS has argued that all aspects of the program are of high priority. There are challenges posed by the need to operate the experiment, construct new detector components and analyze multiple data sets in concomitance with limited staffing resources. The U.S. ATLAS teams have certain obligations within the ATLAS collaboration that need to be met. In particular, tasks related to the successful collection and exploitation of the upcoming data are a top priority. Similarly, activities related to the planned upgrades have an impact on the overall experiment and, possibly, the LHC schedule and thus need to be completed in a timely manner. **A clear articulation of unique contributions to the ATLAS experiment could serve to identify priorities in challenging times. In addition, the committee encourages ATLAS to further pursue synergies with CMS and other experiments that are addressing similar experimental challenges, including detector technologies and computing. Increasing the efficiency of analysis or delaying analyses could also be routes to consider in the prioritization.**

b. CMS Experiment

CMS is a general-purpose hadron collider experiment at the Energy Frontier. The collaboration was responsible (along with ATLAS) for the discovery of the Higgs boson, initially in its decays to bosons, and more recently providing measurements of its couplings to fermions. CMS has also produced many journal publications on measurements of heavy Standard Model particles such as the top quark, W and Z bosons as well as properties of the strong interactions at an unprecedented energy scale, at a proton-proton center-of-mass energy of up to 13 TeV. In addition, CMS has conducted a wide variety of searches for supersymmetry and a wide range of more exotic alternatives to the Standard Model. U.S. CMS has a broad physics program across all of the most critical physics topics on the LHC. The DOE-supported U.S. CMS program includes measurements and results in Higgs physics (*e.g.,* measurements in different production modes, and of its coupling to fermions), beyond Standard Model physics, new interactions, top quark properties, measurements of W and Z, properties of strong interactions, and B physics. **Overall, the U.S. CMS team has a broad footprint and plays a leading role within the international CMS collaboration activities.**

The results of the proposed work will have impact on the direction, progress, and thinking in relevant scientific fields of research. The U.S. CMS science program includes research that overlaps with and stimulates other programs in particle physics, such as searches for dark matter. The discovery by CMS and ATLAS of a fundamental scalar has potential implications in early universe cosmology: while the existence of scalar fields has been commonly assumed in cosmological model building, the discovery of the Higgs boson provides the first known example of such a field. The precision measurement of the top quark mass has an impact on understanding of the stability of the vacuum of our universe. **The U.S. CMS Research program impacts a number of research areas in particle physics. Results and publications for CMS are central to the field of particle physics overall and are therefore followed closely by the rest of the particle physics community, both experimental and theoretical.**

Overall the likelihood of achieving valuable results is high, both for present data sets and those that the upgrades will bring. A concern at the time of the review is failing electronic components (DC-DC converters) on the CMS pixel detector, causing significant loss of pixel detector efficiency at the end of the LHC run in calendar year 2017. After component replacement, the detector should return to full efficiency at the start of data taking in 2018, but, if the same rate of loss continues, the inefficiency may be substantial by the end of the run. CMS is addressing this issue, but it may require significant work in the next long shutdown. Of particular importance is the HL-LHC running period, when the integrated luminosity will increase by about a factor of ten, significantly improving the sensitivity to new physics and the couplings of the Higgs boson. Handling high pile-up is a challenge for the experiment, with currently up to an average of 60 interactions per beam crossing, which will increase up to an average of 200 at the HL-LHC. The HL-LHC (Phase-II) detector upgrades are essential to survive the high luminosity and radiation levels the detector will experience during the HL-LHC period. Proposed U.S. CMS contributions include the Tracker upgrade, the High Granularity forward calorimeter, and precision timing for all charged tracks (although the latter is still under discussion and awaiting approval through the necessary CERN processes). The DOE-supported part of the collaboration will deliver approximately 50% of the trigger electronics, 20% of the data acquisition system for the upgrade, and 30% of the outer tracker detector. The committee notes that funding the timing detector under the upgrade project may impact other components already contained in the project. **As the integrated luminosity increases in Run 3, including the Phase-I upgrades, with long runs and increasing accelerator performance, the potential for discoveries of new weakly interacting particles improves; enhancements in precision measurements are also enabled. The U.S. CMS contributions are critical for the overall success of the CMS HL-LHC upgrades.**

Obtaining the necessary level of computing capability for the HL-LHC era is recognized to be a major challenge in the context of both the numbers of interactions per crossing and the evolution of heterogeneous computer architectures. CMS is doing R&D work on computing with HPC platforms, however, there has not been sufficient progress to take advantage of these resources. Optimization studies will need to continue in order for workflows to better handle event generation, detector simulation, event reconstruction, and analysis. The hardware/software balance may need to change to exploit these multiple approaches. **The computing model will need to be transformed, to accommodate the increase in data and simulation expected from the coming runs and the HL-LHC upgrade. This challenge is exacerbated by the complexity of the event environment.**

The proposed research, both in terms of scientific and technical merit and originality, compares well with other experiments which address the same physics. The productivity in terms of scientific results can be illustrated by the number of papers that CMS has published, which is, at the time of the review, over 700 papers in total, at a rate of about 100 per year. **The CMS program is excellent: along with ATLAS, the experiment is a world-leader at the Energy Frontier. In terms of technology, CMS has pushed the frontiers for large-area silicon detectors and crystal calorimetry, and the scientific output by the collaboration is impressive.**

On the data analysis front, a framework of standard physics objects with well-measured systematic errors and analysis with high level scripts has been developed. It should therefore be possible to develop an analysis framework that would allow a university group with a professor/Principal Investigator and a postdoc or a professor and a graduate student to carry out a full physics analysis. This may seem difficult for a hadron collider experiment; however, an existence proof is available from LHCb. In addition to improvements in efficiency and reduction of duplicate efforts, an advantage of this approach would be to allow the CMS experiment to cover a broader range of new physics signatures (some of which are currently at lower priority due to lack of people and/or perceived lack of potential). Since supersymmetry was not discovered in the first runs of the LHC, it is important to maintain an open viewpoint for physics analysis without theoretical prejudice and fully explore a variety of physics signatures. **Improved communication and synergies with ATLAS could produce significant benefits. Areas of**

cooperation may include Monte Carlo generators, Application Specific Integrated Circuit (ASIC) and firmware development for fast-timing detector technology and Grid computing middleware with distributed data management.

The experiment has been effective in training and mentoring students and junior researchers. U.S. CMS is hosted by a single national laboratory, Fermilab, and contains 36 DOE-supported university groups. In addition, NSF supports the contribution of 17 universities. Over the past four-year period and up to the time of this review, CMS trained 282 PhDs, 472 Graduate Students, and 582 Undergraduates. Programs for junior scientists are run through the LHC Physics Center (LPC) at Fermilab for training (*e.g.,* CMS data analysis school, hands-on tutorials, LPC help-desk, regular workshops with ATLAS), with mentoring for leadership roles for jobs in academia and industry. Their training for work in HEP (and the skillset developed) prepares students and postdocs both for academia and for data science/industry. **The proposed U.S. CMS research plan will deliver significant productivity in terms of student and postdoctoral fellow training. However, the committee sees a need for improved coordination and communication (such as seminar series, etc.) to help young people find career paths inside and outside of academia. The U.S. CMS groups could also be more proactive both with respect to tracking where students and postdocs go after their time on CMS, and the professional development for those who will transition to careers in industry.**

U.S. CMS stated that over the next four years, staffing needs will be constant; an increase in FTEs needed for upgrade work will be compensated by efficiencies found in analysis tasks. The breakdown of the required staffing level is as follows: for U.S. CMS detector operations (95 FTE), U.S. CMS computing (31 FTE), physics service work (80 FTE), detector upgrades (115 FTE), physics data analysis and publications (90 FTE). U.S. CMS supports approximately 545 PhD physicists, 312 graduate students, 285 engineers and technicians. During presentations by U.S. CMS, the breakdown of effort between DOE and NSF was, however, not made clear to the panel. **The proposed staffing levels appear to be well matched to the proposed work, for each of the top science and technology goals. CMS computing appears to benefit greatly from leveraging resources from the Fermilab Scientific Computing Division (SCD). There is a reasonable balance between the roles of physicist, graduate student, engineer and technician for the proposed work in the next four years.**

U.S. groups are involved in all the top science and technology goals of CMS including the science drivers, data preparation and fundamentals of the Standard Model, and R&D for upgrades on the systems for which they are responsible. U.S. CMS holds leadership positions in physics analysis, with approximately 41% of the analysis contacts, and in management and group convenorships, with 16 FTE in CMS management, including two out of the last four CMS collaboration spokespersons. Three of the recent CMS physics coordinators were from the U.S., as well as approximately 35% of physics analysis group conveners, and 44% of analysis review committee chairs. **The U.S. is capitalizing on its investment very effectively. Some additional coordination**

within U.S. CMS amongst physics topics may benefit the scientific output of U.S. CMS while continuing to ensure alignment with the P5 science drivers.

U.S. CMS brings a number of capabilities and facilities to CMS and the LHC. In the field of technology, this includes silicon detectors, handling 8-inch silicon wafers, ASICs and FPGAs. In computing, this includes the development of HPC and Grid computing infrastructure, and the close connection to and collaboration with the Fermilab SCD. In physics: utilizing jet substructure to enable new physics, searches for long-lived charged particles, searches for supersymmetry, and for dark matter in missing-energy channels. These efforts have benefitted from a close collaboration with the U.S.-based theory community. Proton beam tests will be possible at Fermilab, including the time during CERN accelerator shutdowns, to understand detector response. **U.S. CMS is taking advantage of strong and special capabilities which have significant impact on CMS overall. The role of Fermilab, as the single center for U.S. CMS in the United States, is excellent. As Fermilab develops its laboratory program in the Intensity and Cosmic Frontier programs, its continued support for U.S. CMS is essential.**

The experiment was asked to consider the impact that a reduction of DOE funding would have on research and operations. Since university groups would not wish to compromise their physics output, or their responsibilities for detector operations, a potential concern is that they may reduce their effort on the upgrade, thus jeopardizing the long-term future of the experiment. Computing is currently a more significant contribution than its fair-share, as approximately 40% of the Tier-1 computing resources for international CMS come from U.S. CMS DOE-HEP support (cf. the U.S. CMS team is approximately 29% of the collaboration), suggesting that a rebalancing could be advantageous. CMS does exploit synergies both within the experiment and with ATLAS, and across the LHC program in general. Possible areas for enhancement include computing, timing detector technology, and ASIC development for the upgrade. **Obtaining good data on tape must be the absolute priority. The HL-LHC upgrade cannot be delayed too long because of the eventual reduction in performance of the existing detector in the high radiation environment, along with the need to remain in step with the accelerator upgrades, and with international obligations. Increasing the efficiency of analysis, or possibly delaying analyses, could be routes to consider. Synergies should continue to be exploited as much as possible to increase efficiency. U.S. CMS, supported by DOE, could explore the potential for its computing contributions to international CMS to reduce its operations obligations.**

c. Program-Wide Considerations

The LHC continues to operate well. During the past two years, Run 2, the collider has surpassed the design luminosity; it is currently running at 13 TeV, with every expectation that in Run 3 it will match that luminosity but at 14 TeV. The program is broadly recognized as preeminent within the world of particle physics. The DOE scope in each of the general-purpose experiments, ATLAS and CMS at the LHC, is greater than that of any individual collaborating country. The technical contributions based on DOE funding are critical to the success of the experiments. Both experiments also, in the main, continue to operate well, and to produce new results. These results span the space from the W boson to Higgs boson and top quark, and the search for physics beyond what we currently know. If there is new physics beyond the Standard Model at the TeV scale, accessible from proton-proton collisions, it is likely that ATLAS or CMS will find it in one of their searches. The alignment with the vision of P5 is evident. Further, the participation of DOE-supported researchers in high-level leadership positions that influence the direction of the experiments also matches or exceeds the pro-rata expectations. **Overall, the U.S. ATLAS and U.S. CMS support places the DOE Energy Frontier research program in a world-leading position within particle physics.**

Large-scale computing is key to the LHC data analysis, and this aspect was discussed in each of the experiment-dedicated sections above and, modulo some nuances, is a common issue. It was pointed out that the data currently in hand represent only a few percent of the eventual yield from high luminosity LHC (HL-LHC) running. Once again the challenge going forward will be formidable. It is no longer anticipated that computing power will expand in a simple way as during the years when Moore's Law held. Over the next two decades, benefitting from the future computing developments will depend on the ability to exploit heterogeneous computing environments and changing architectures. The community has produced several reports addressing a number of these issues. The committee notes that the DOE intends to invest significantly in HPC[4]. This will lead to systems that, in principle, have the raw performance to meet the U.S. computational requirements for HL-LHC. Starting in approximately 2020-2021 onwards, however, no major DOE ASCR/Leadership computing system will have a significant fraction of its computational power coming from conventional CPU cores. To use these systems effectively, and in the context of, perhaps different, international trends, will require a major refactoring of current HEP codes. In addition, the multiple architectural approaches are expected to continue to evolve on relatively short timescales. Portability will therefore be an essential design requirement of the future HEP code base, whether it is targeted at HPC systems or not. **The panel strongly encourages U.S. ATLAS and U.S. CMS to pursue a software R&D program as well as to consider evolving the overall computing model in response to future changes in the**

[4] The Exascale Computing Project is a collaborative effort of two U.S. Department of Energy organizations, the Office of Science and the National Nuclear Security Administration, to meet the science and national security mission needs of the DOE. Additional information is available online at: https://www.exascaleproject.org/.

computational infrastructure, including both storage and networking. In view of the critical role of data handling and processing to the success of these programs, this challenge should not be underestimated.

Both experiments described their analysis processes in some detail. The importance of experiment-wide approaches to data reduction and object identification and calibration, even to statistical treatments was emphasized. Nevertheless, perhaps as a result of the increasingly harsh environment with increasing numbers of interactions per crossing, this has not led to a reduction in analysis effort per physics result and publication. Given the pressure on the resources available for physics analyses the status quo may be difficult to maintain. **We continue to dream of the small university-based group led by a faculty member being able to do a complete analysis. The development of a new analysis paradigm, through some major transformation of the current approach, which also facilitated access to the results by the theoretical community, would be highly desirable.**

The headlines that catch the attention of the general population, and indeed what motivates physicists, usually concern a physics discovery, the revelation of a new insight into, or understanding of, our world. However, behind these discoveries are people, and in the case of ATLAS and CMS, large numbers of people. Hundreds of students supported by the DOE Office of High Energy Physics train for their doctorates on these two large experiments. The breadth of experience, the opportunities to work with high technology, both hardware and software, and the intellectual challenges encountered are perhaps unique. This implicit education can also be enhanced, for example in the collaborative atmosphere of the LHC Physics Center at Fermilab, and indeed in periods of residence close to the experiments at CERN. In turn the experiments could not function without the contributions of students and their postdoctoral colleagues. Some junior scientists stay within academia, but many enter the broader society, contributing in diverse ways. Providing a good experience serves society well and will attract the brightest and best to this important endeavor. **The explicit attention paid to the development of junior participants in a diverse and inclusive environment by the U.S. ATLAS and U.S. CMS collaborations is very important; further enhancement of such activities should be considered.**

One way of improving the productivity per unit of funding is to be able to share the results of the funding across multiple endeavors. This can be done by identifying synergies and the subpanel was pleased to hear of such synergies. There are certainly examples in the electronics, and electro-optical regime, where the same boards or chips are used in both experiments. We also understand that there is cross-pollination in the software arena. The subpanel would like to indicate that there are further opportunities of this ilk. We also note that at BNL there is a developing collaboration involving computing for Belle II in conjunction with that for ATLAS. We might expect that synergies, with, for example, astro-particle physics, could also bear fruit. **The experiments should consider the opportunities to more aggressively exploit the synergies.**

The size of the DOE fraction of the ATLAS and CMS experiments is large. Many of the scientists and most of the students come from leading universities in the United States. The collaborations exploit the facilities and capabilities at five (out of ten) of the DOE Office of Science National Laboratories, giving them access to a wide set of capabilities. A leading example is computing. For both experiments, the Tier-1 facilities, ATLAS at Brookhaven National Laboratory and CMS at Fermilab, are the top performers in their respective experiments. Over the past few years the introduction of HPC has also been led by DOE-supported researchers. At Fermilab, facilities, for example, developed for the Tevatron experiments, such as the Silicon Detector facility, are as big as any in the world and this special facility has had a major influence on the CMS experiment. In conversation with the other collaborators within the larger ATLAS and CMS collaborations, the influence of DOE leadership is highly valued. These aspects are evident within the field of particle physics; however, it is important that they be recognized more broadly. **It is important that the collaborations consider, discuss, and share the impacts of their work with a wide spectrum of audiences that range from the broad scientific community, to policy makers, and to "people-on-the-street".**

3. Conclusions

The DOE Energy Frontier program embodied in the general-purpose experiments, ATLAS and CMS at the LHC, is a vital component of the global particle physics program. It is also a vital component of the respective international experiments themselves.

The contributions of this program to the experiments and its overall impact is substantial; in scale, it exceeds that of any other single country. The contributions of the U.S. effort, while broad, are distinct and identifiable. The effort exploits the special facilities available through the national laboratories of the DOE Office of Science and the supported universities. The intellectual leadership of the U.S. groups is manifest within the experiments.

The programs have paid attention to the need for efficient use of resources, this is most evident in the Operations and Computing programs, where the current level of resources was largely justified. In the Research Program, experiment management participates with a lighter touch in the physics direction and priorities of individuals and groups. Nevertheless, the physics accomplishments of the groups are dominated by topics that were highly regarded in the 2014 P5 strategic plan. In the general area of productivity, the subpanel encourages strongly increased exploitation of potential synergies, and possible innovative approaches to the whole analysis enterprise. More attention could be paid to the career development of young participants within the collaboration.

The subpanel was asked to consider this assessment also in the context of a volatile budget situation. This is always a difficult subject exacerbated by out-year uncertainties. The general sense of the subpanel was that a modest reduction in support could compromise the roles and effectiveness of U.S. DOE groups, through the delay or even loss of some physics analyses, and might also affect the HL-LHC detector upgrades. Further, the committee had the sense that a significant reduction would prompt an undesirable re-discussion of the levels of commitment in all of Research, Operations, Computing, and even the Detector Upgrade Project, to ensure an optimally strategic response.

The U.S. ATLAS and U.S. CMS programs are distinctive and excellent; the experiments are world-leaders at the Energy Frontier of particle physics, and a strong future, spanning the next two decades, is foreseen.

Acknowledgements

The subpanel would like to acknowledge the logistical support, assistance, and detailed quality assurance provided by the staff of the Office of High Energy Physics in the DOE Office of Science in the preparation of the report. In particular, Abid Patwa provided extensive factual accuracy reviews and Michael Cooke led the layout of the report.

Appendix A: Review Charge

U.S. Department of Energy
and the
National Science Foundation

OCT 13 2017

Dr. Andrew Lankford
Chair, HEPAP
University of California, Irvine
4129H Frederick Reines Hall
Irvine, California 92697

Dear Dr. Lankford:

The Department of Energy (DOE) Office of High Energy Physics (HEP) requests that the High Energy Physics Advisory Panel (HEPAP) charge subpanels to conduct an independent peer review of currently operating experiments supported by HEP [hereafter generically referred to as "HEP experiments"]. This review should focus on the scientific impact and productivity of HEP-supported contributions to these experiments within the context of the overall HEP portfolio. HEP will use the findings and recommendations from this review to help further define a detailed implementation plan for the strategic vision laid out in the Particle Physics Project Prioritization Panel ("P5") Report, as recommended by the recent HEP Committee of Visitors.

This review process is modelled in part on similar "Senior Review" or "Portfolio Review" processes employed by the National Aeronautics and Space Administration and the National Science Foundation to maximize the scientific productivity of their respective mission or facility portfolios within realistic budget constraints, with modifications as needed and appropriate for the DOE mission and experimental portfolio. Therefore, this independent review will serve primarily as advice to HEP. Specifically, HEP will use the outcomes from this process to:

- Prioritize the currently operating HEP portfolio of experiments (including contributions to HEP experiments at off-shore facilities);
- Define an implementation approach to best achieve the goals of the P5 science drivers; and
- Provide programmatic guidance to the HEP experiments concerned for FY 2019 and beyond.

Additional outcomes or programmatic guidance for future years may be provided to the experiments at the discretion of HEP management. Actions resulting from this review process could include changes to research support; extending the planned running of a particular experiment; maintaining the status quo; significantly restructuring the run plan; or terminating HEP support for experimental operations. **All currently-supported HEP experiments that have taken physics data for at least two years, and are expected to request significant DOE support for operations, or related activities (e.g., computing) beyond FY 2018 are subject to this review.**

This letter describes the general objectives and process to be used for this review. Separately, HEP will issue a call for proposals to the lead Principal Investigators, Spokespersons, and/or Institutional Boards for the relevant experiments listed below so that they can address the elements of this charge and the relevant review criteria in a common format. For international collaborations, the appropriate DOE-supported institutional lead(s) should prepare a response, in coordination with international collaboration management, which focuses on the DOE science deliverables as outlined below.

Each experiment that is invited to the HEP Portfolio Review will submit a proposal outlining its primary science goals for the next four years and describing how its research program will benefit the HEP science drivers described in the P5 Report. Performance factors to be assessed will include:

- Science merit and productivity (including training and mentoring of junior researchers),
- Present and anticipated future impact on the P5 science drivers, and
- Efficiency and impact of DOE-supported contributions to the research efforts.

Operations budgets and schedule information will be requested from proposers but will not be an explicit review criteria. DOE will provide additional information about DOE responsibilities and budget scenarios to the review panels.

All operating experiments (as defined above) should be comparatively assessed by a single subpanel, with suitable exceptions for the highest priority items identified in the P5 plan. Therefore, we request two subpanels be formed as follows:

1. The main subpanel: This comparative review panel will assess the scientific merits and impact of DOE-supported contributions to the following operating experiments (in alphabetical order): AMS, Daya Bay, DES, eBOSS, Fermi/GLAST, HAWC, K0TO, MicroBooNE, Minerva, NA61/SHINE, NOvA, SuperK, T2K.

2. The LHC Detectors (ATLAS, CMS) subpanel: This review panel will assess the scientific merits and impact of DOE-supported contributions to the multipurpose LHC detectors ATLAS and CMS. These detectors have been successfully operating since 2008, and other than recent modest upgrades, there have been no major changes to the initial detector configurations. Major detector upgrades for the High Luminosity phase of the LHC program (HL-LHC) are in the advanced planning stages, and U.S. groups have taken important roles in the detector upgrade projects. Given its centrality in the global HEP vision enunciated in the P5 Report, and the high priority placed on this program by HEPAP, DOE intends to support LHC operations and research through the HL-LHC era. U.S. contributions to LHC detector operations are regularly reviewed by the DOE and the NSF in a separate process. Therefore, this subpanel will focus primarily on the efficiency and impact of DOE-supported contributions to ATLAS and CMS research efforts.

A call will be issued in parallel with this charge, along with the specific review criteria for each subpanel to consider, and proposals are expected to be due in November. The subpanels should meet expeditiously so that their final reports can be delivered to HEPAP no later than April 2018. HEPAP will review these reports and communicate its findings and recommendations to DOE.

After HEPAP makes its recommendations, DOE/HEP will contact each of the experiments and communicate guidance resulting from the HEP Portfolio Review. This direction may include new budget guidelines and other specific instructions resulting from the Portfolio Review process, possibly including notices of intent to terminate DOE involvement. DOE/HEP will also post the HEPAP subpanel reports and its response to the HEPAP website. Each of the experiments will submit back to DOE/HEP their plan for complying with the new guidance and instructions. HEP management will ensure that key officials in institutions or agencies that are partners in operating experiments are apprised of DOE's decisions resulting from the HEP Portfolio Review.

We anticipate that this review process will allow DOE the ability to periodically rebalance its HEP experimental portfolio, and adapt as needed to different budget scenarios. We feel the participation of HEPAP is critical in this important process and very much appreciate your timely consideration of these proposals. We look forward to lively and fruitful discussions of this topic at future HEPAP meetings.

Sincerely,

J S Binkley

J. Stephen Binkley
Acting Director
Office of Science

James S Ulvestad

James S. Ulvestad
Assistant Director (Acting)
Mathematical and Physical Sciences
National Science Foundation

Appendix B: LHC Subpanel Membership

Marina Artuso	*Syracuse University*
Tom Browder	*University of Hawaii*
Bonnie Fleming	*Yale University*
Roger Forty	*European Organization for Nuclear Research (CERN)*
Hassan Jawahery	*University of Maryland*
Kay Kinoshita	*University of Cincinnati*
Salman Habib	*Argonne National Laboratory*
Tao Han	*University of Pittsburgh*
Klaus Honscheid	*Ohio State University*
Hugh Montgomery	*Thomas Jefferson National Accelerator Facility*
Kevin Pitts	*University of Illinois at Urbana-Champaign*

Appendix C: Meeting Sessions of the LHC Subpanel

HEP Portfolio Review – LHC Subpanel Session
Agenda

Monday, February 26, 2018
Hilton Rockville – Regency Room

Item	Time	Session and Description
1	07:00 – 08:00	Continental Breakfast – Outside Lobby of Regency Room [Panelists]
2	08:00 – 09:00	Executive Session: Introductions and Discussion of Process – No Call-In [Panel and DOE-agency only]
3	09:00 – 10:30	LHC Collaboration #1: ATLAS – Presentations (with ATLAS Call-In)
4	10:30 – 10:45	Break
5	10:45 – 11:45	Executive Session – Discussion of Collaboration #1 [ATLAS] Presentations; Questions – No Call-In [Panel and DOE-agency only]
6	11:45 – 12:30	Discussion of Questions, Verbal Clarifications with Collaboration #1 [ATLAS]; (with ATLAS Call-In)
7	12:30 – 13:30	Working Lunch
8	13:30 – 15:00	LHC Collaboration #2: CMS – Presentations (with CMS Call-In)
9	15:00 – 15:15	Break
10	15:15 – 16:15	Executive Session – Discussion of Collaboration #2 [CMS] Presentations; Questions – No Call-In [Panel and DOE-agency only]
11	16:15 – 17:00	Discussion of Questions, Verbal Clarifications with Collaboration #2 [CMS]; (with CMS Call-In)
12	17:00 – 17:15	Break
13	17:15 – 18:15	Executive Session; Discussion Towards Conclusions – No Call-In [Panel and DOE-agency only]
14	Evening	Dinner

all times are in U.S. Eastern Standard Time

LHC Collaboration #1: ATLAS Collaboration
LHC Collaboration #2: CMS Collaboration

Tuesday, February 27, 2018 – Panel and DOE-agency only
Hilton Rockville, Rockville Maryland – Regency Room;
LHC Subpanel Deliberation and Report Preparation

Second LHC Subpanel Session: In-person Meeting
Monday, March 26, 2018 – Panel and DOE-agency only
Hilton Rockville, Rockville, Maryland – Regency Room;
Follow-up for LHC Subpanel Report Preparation (in-person meeting)

Appendix D: Acronyms, Abbreviations, and Glossary

ANL	Argonne National Laboratory (Illinois)
ASCR	Advanced Scientific Computing Research
ASIC	Application Specific Integrated Circuit
ATC	ATLAS Center
ATLAS	A Toroidal LHC ApparatuS
Belle II	Particle physics experiment to study B mesons at SuperKEKB accelerator complex (Tsukuba, Japan)
BNL	Brookhaven National Laboratory (New York)
CERN	European Organization for Nuclear Research
CMS	Compact Muon Solenoid
CPU	Central Processing Unit
D.C.	District of Columbia
DC-DC	Direct Current to Direct Current
DOE	Department of Energy
Eng	Engineering
ESU	European Strategy Update
eV	electron Volt (the energy gained by an electron falling through a 1 Volt potential difference)
EYETS	Extended Year-End Technical Stop
fb^{-1}	inverse femtobarns
Fermilab	Fermi National Accelerator Laboratory (Illinois)
FNAL	Fermi National Accelerator Laboratory (Illinois)
FPGA	Field-Programmable Gate Array
FTE	Full-Time Equivalent
FY	Fiscal Year
HEP	High Energy Physics
HEPAP	High Energy Physics Advisory Panel (to DOE and NSF)
Higgs boson	Elementary particle in the Standard Model; discovered in 2012 at CERN
HL-LHC	High-Luminosity Large Hadron Collider
HPC	High Performance Computing (large-scale supercomputing clusters)
KEK	Kō Enerugī Kasokuki Kenkyū Kikō (High Energy Accelerator Research Organization; Tsukuba, Japan)
LBNL	Lawrence Berkeley National Laboratory (California)
LHC	Large Hadron Collider
LHCb	LHC beauty Experiment

LPC	LHC Physics Center
LS1	Long Shutdown 1 (2013-2014)
LS2	Long Shutdown 2 (2019-2020)
LS3	Long Shutdown 3 (2024-2026)
MC	Monte Carlo (scientific simulations)
Moore's Law	Observation made by Gordon Moore in 1965 on the growth rate of number of transistors on integrated circuit chips
NSF	National Science Foundation
NSW	New Small Wheel
ORNL	Oak Ridge National Laboratory (Tennessee)
P1-P5	Point-1 (ATLAS Experiment, Switzerland) and Point-5 (CMS Experiment, France)
P5	Particle Physics Project Prioritization Panel (Subpanel of HEPAP)
Phase-I	Initial LHC Detector Upgrades (for installation in LS2)
Phase-II	High-Luminosity LHC Detector Upgrades (for installation in LS3)
R&D	Research and Development
R2E	Radiation to Electronics (CERN)
SCD	Scientific Computing Division (Fermilab)
SLAC	SLAC National Accelerator Laboratory (California)
SM	Standard Model of Particle Physics
STEM	Science, Technology, Engineering, and Mathematics
SuperKEKB	Particle accelerator complex located at the KEK Research Organization (Tsukuba, Japan)
SUSY	Supersymmetry
TeV	Tera (Trillion) eV
Tevatron	Circular particle accelerator in the United States at Fermilab; operated during 1983-2011
Tier-1	First Level of Computing Centers in the Worldwide LHC Computing Grid (for LHC data)
Tier-2	Second Level of Computing Centers in the Worldwide LHC Computing Grid (for LHC data)
U.S.	United States
U.S. ATLAS	The U.S. Collaborating Members and Institutes in ATLAS
U.S. CMS	The U.S. Collaborating Members and Institutes in CMS
W boson	Electrically charged elementary particle, discovered in 1983 at CERN; along with its cousin Z boson, carries weak force
Z boson	Neutral elementary particle, discovered in 1983 at CERN; along with its cousin W boson, carries weak force

High Energy Physics Advisory Panel Transmittal Letter

SLAC NATIONAL ACCELERATOR LABORATORY

FUNDAMENTAL PHYISCS DIRECTORATE

JoAnne Hewett
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November 28, 2018

Dr. J. Stephen Binkley
Acting Director
Office of Science
U.S. Department of Energy

Dr. Anne L. Kinney
Assistant Director
Mathematical and Physical Sciences
National Science Foundation

Dear Dr. Binkley and Dr. Kinney,

The report of the HEPAP Subpanel on the LHC Detectors for a portfolio review of DOE Office of High Energy Physics operating experiments was presented to HEPAP at its meeting on May 14, 2018. This subpanel was one of two formed to deliver reports addressing the charge in your letter of October 13, 2017 for HEPAP to assemble subpanels "to conduct an independent peer review of currently operating experiments supported by DOE Office of HEP," with a "focus on scientific impact and productivity of HEP-supported contributions to these experiments within the context of the overall DOE HEP portfolio."

At the HEPAP meeting, the LHC Detectors Subpanel chair Dr. Hugh Montgomery summarized the major findings of the review and responded to questions from HEPAP members. A draft of the written report had been circulated to HEPAP prior to, and in order to prepare for, the HEPAP meeting. Following discussion and deliberation, HEPAP unanimously endorsed the LHC Detectors Subpanel report without objection. Subsequent to the HEPAP meeting, the subpanel has prepared, and HEPAP has endorsed, the final report, which is attached.

The review process was greatly aided by the extensive and detailed information provided in advance by the LHC Detector U.S. Collaborations. The review was expertly performed and documented by the subpanel and I thank the subpanel members on behalf of HEPAP.

With this letter, on behalf of HEPAP, I respectfully submit for your consideration the final report of the HEPAP LHC Detectors Subpanel for review of U.S. DOE contributions to operating experiments at the LHC.

Sincerely,

JoAnne L. Hewett

JoAnne L. Hewett
Chair, High Energy Physics Advisory Panel

A U.S. Department of Energy Research Facility Operated Under Contract by Stanford University