Mission Need Statement
for

HL-LHC ATLAS and CMS Detector Upgrades

Non-Major Acquisition Project

Office of High Energy Physics
Office of Science
U.S. Department of Energy

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Mission Need Statement
HL-LHC ATLAS and CMS Detector Upgrades

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1. STATEMENT OF MISSION NEED

The mission of the Department of Energy (DOE) is to advance the energy, environmental, and nuclear security of the United States; promote scientific and technological innovation in support of that mission; and ensure the environmental cleanup of the national nuclear weapons complex. The DOE Strategic Plan 2014–2018 includes the following goals and objectives that are relevant to this mission:

Goal 1: **Science and Energy**	*Strategic Objective 3 – Deliver the scientific discoveries and major scientific tools that transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation.*

The mission of the Office of Science (SC) is to deliver the scientific discoveries and major scientific tools that transform our understanding of nature and advance the energy, economic, and national security of the United States. SC accomplishes this mission through direct support of research, construction, and operation of national scientific user facilities, and the stewardship of ten world-class national laboratories. The SC national laboratories collectively comprise a preeminent federal research system that develops unique, often multidisciplinary, scientific capabilities beyond the scope of academic and industrial institutions, to benefit the nation's researchers and national strategic priorities.

The mission of the High Energy Physics (HEP) program is to understand how the universe works at its most fundamental level by discovering the elementary constituents of matter and energy, probing the interactions between them, and exploring the basic nature of space and time. Our current understanding of the elementary constituents of matter and energy is captured in what is called the Standard Model of particle physics. It describes the elementary particles that comprise ordinary matter and the forces that govern them with very high precision.

The experimental HEP program is focused on three frontiers of scientific discovery: the Energy, Intensity, and Cosmic Frontiers. At the Energy Frontier, powerful accelerators are used to create new particles, reveal their interactions, and investigate fundamental forces. The only Energy Frontier facility presently operating is at the European Organization for Nuclear Research (CERN), which hosts the Large Hadron Collider (LHC). As the largest particle physics laboratory in the world, CERN has twenty-one Member States and is located near Geneva, on the border of Switzerland and France. The U.S. has been a major partner in the LHC since its inception. The DOE HEP and NSF Experimental Elementary Particle Physics (E-EPP) programs provided major contributions to construction of detector subsystems for the two large general-purpose detectors at the LHC: A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS). Experiments at the LHC completed their first successful run in 2012 that highlighted the discovery of the long-sought Higgs boson particle, recognized by the 2014 Nobel Prize in Physics. In May 2015, CERN and the U.S. signed a scientific and technical cooperation agreement that renewed the framework for continued U.S. involvement in the LHC program.

In September 2013, the DOE and the National Science Foundation (NSF) charged the High Energy Physics Advisory Panel (HEPAP) to convene a Particle Physics Project Prioritization Panel (P5) in order to develop a ten-year strategic plan for U.S. high energy physics in the context of a 20-year global vision. In May 2014, HEPAP unanimously approved the P5 report and its recommendations. The report provides a practical, long-term strategy that enables discovery and maintains the U.S. position as a global leader in particle physics. The DOE accepted the recommendations in the P5 report and is committed to implementing a successful program based on this new vision. Consistent with the P5 report, a centerpiece of the HEP program strategy is exploration of the Energy Frontier at the LHC. The high energy and luminosity available at the LHC offers the best opportunities for exploration of new physics beyond the Standard Model and for making precision measurements of properties of known phenomena.

At the present time, each of the ATLAS and CMS experiments are undergoing an intermediate upgrade that will be completed in 2019 in order to allow the detectors to continue efficient performance during complex machine running conditions. The experiments are therefore poised to extend the discovery potential that will change our fundamental understanding of nature. As identified by the 2014 P5 plan, continuing strong U.S. participation in the full exploitation of the LHC is an integral part of the U.S. HEP program. Currently, approximately 1,200 physicists from U.S. institutions conduct research as collaborators on ATLAS and CMS, and an additional 400–500 technical staff and engineers lead operations for the experiments as well as design and build critical components for the detectors. These collaborators are mainly supported through parts of the DOE HEP research and operations programs and have distinct roles that include design, delivering, operating detectors, and analyzing and producing new physics results. Given the broad experience gained during both the original construction project and the ongoing LHC runs, U.S. physicists, technicians and engineers are in a unique position to contribute to the future LHC program in the best possible way while maintaining the leadership role the U.S. has had over the past two decades.

2. CAPABILITY GAP/MISSION NEED

The LHC accelerates two beams of proton bunches, which circulate in opposite directions, and collide head-on at very high energies and thereby allow for the creation of new particles. The luminosity, or equivalently the number of protons in each beam colliding per second, is planned to gradually increase during the course of LHC operations resulting in a higher number of collisions and thus an increased probability for exciting new discovery capabilities. Further, each bunch crossing is expected to produce a number of proton collisions that will result in an enormous number of particles at the beam interaction point. Such conditions are often characterized by the number of interactions per bunch crossing, commonly referred to as 'pile-up'. The long-term upgrade plans for the LHC will provide a machine with significantly higher luminosity. Consequently, the collider's higher performance will create harsh physical environments for the existing detectors, which, if not upgraded, will result in a capability gap.

The LHC successfully completed its initial three-year run in 2012 (Run 1) at center-of-mass energies of 7–8 TeV, reaching a peak luminosity of 7.7×10^{33} $cm^{-2}s^{-1}$ and resumed operations in 2015 (Run 2) at energies of 13–14 TeV with planned increases to luminosities of $2\text{–}3 \times 10^{34}$ $cm^{-2}s^{-1}$ through 2023 (Run 3).

A High Luminosity upgrade of the LHC (HL-LHC) is planned to begin operations in the second half of 2026. After the upgrade, each detector is expected to integrate 3,000 fb^{-1} of data per run, compared to 300 fb^{-1} of data during the run immediately prior to the HL-LHC upgrades. This will be accomplished through two techniques: the peak luminosity will be increased by a factor of two, and the decay of the luminosity while the beam is in store for a certain period will be slowed to a level that will raise the average luminosity delivered to the experiments by a factor of about five.

The pile-up conditions are expected to be factors of 5–8 times higher than those presently seen at the LHC. In order to operate for an additional decade within this challenging physical environment, both the ATLAS and CMS detectors require upgrades to their aging inner trackers, the muon systems, the calorimeter systems, and the trigger and data acquisition systems.

Tracking Systems: The innermost portions of the tracking systems of both detectors play a key role in the identification of primary vertices, secondary vertices, and secondary tracks. These elements are essential for the efficient identification of long-lived particles, such as *b* quarks, and for the search for new physics at the LHC. The need to upgrade the inner trackers is driven primarily by radiation damage caused by particles produced at the collision point under intense beam environments, thereby severely compromising tracking performance. Entirely new finely segmented inner trackers are needed to replace the degraded present detectors. They will need to be more radiation tolerant to minimize future damage. Moreover, the upgrades need to increase readout speeds to handle the increased data rates expected at higher luminosities. The new trackers should be higher performing in order to successfully measure charged particle tracks in a more challenging environment.

Muon Detector Systems: The muon detector systems need to improve the triggering abilities to handle the high luminosity. Higher precision spatial measurements and faster readout electronics will allow the systems to more efficiently reject fake muons and keep the trigger rates manageable at the higher luminosity.

Trigger and Data Acquisition: The present trigger and data acquisition (DAQ) systems will need significant modifications to operate at the higher LHC luminosity. Upgrades to the triggers are motivated by the need to retain trigger capability at lower thresholds to maintain physics acceptance. Improved triggers that can utilize additional information to select interesting signal events in high pile-up environments will be needed. The DAQ will be designed to handle increased data rates and better data flow.

Calorimeters: Portions of the calorimeters of both detectors may need to be replaced to handle the higher pile-up conditions and major portions of the calorimeters of both detectors will need to provide additional information to the trigger in order to allow more selective triggering in the higher luminosity environment.

The present ATLAS and CMS detectors, including the U.S. supplied components, are not capable of handling the higher luminosities and data rates of the LHC expected in 2026 and beyond without the planned upgrades. The overall ATLAS and CMS physics programs can only succeed if the necessary upgrades are implemented; thereby ensuring that high efficiency for expected physics is maintained as luminosity and pile-up increases beyond current design.

HEP supports both the U.S. ATLAS and U.S. CMS collaborations in the international ATLAS and CMS collaborations, respectively. Since each experiment is in a similar circumstance, upgrades for each are required to operate during the HL-LHC running period. There are no other capabilities worldwide capable of addressing the physics results from ATLAS and CMS. In fact, the ATLAS and CMS detectors were purposely designed to provide a "check" on each other's scientific results, and both upgrades are deemed essential to meet mission need.

The DOE's High Energy Physics program has invested in the building of both the ATLAS and CMS detectors, and DOE HEP is a major participant and contributor in the physics the detectors enable. The ATLAS and CMS detectors were built by international collaborations with contributions proportional to the fractional membership of each representative country comprising the collaboration. If the U.S. fails to contribute to the HL-LHC upgrades, their ability to participate in future physics would be impaired.

In 2014, the HEPAP/P5 strategic plan identified continued U.S. participation in the LHC physics program as crucial and specifically recommended support for the HL-LHC upgrades as the highest priority large-category project for the U.S. HEP program in the near-term.

Support of the ATLAS and CMS detector upgrades at the HL-LHC would enable the U.S. community to remain at the forefront of science and the continued pursuit of the prime mission of HEP.

3. POTENTIAL APPROACH

In May 2014, the Particle Physics Project Prioritization Panel (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP) released its report on the strategic plan for HEP. The P5 plan for Energy Frontier recommended that the U.S. actively continue its participation in the LHC program at CERN, and specifically, in the planned HL-LHC upgrades, designating it as the "highest-priority near-term large project". The recommendation is motivated by the fact that the HL-LHC will offer unique physics opportunities that address key science drivers identified by P5 for particle physics. This Mission Need documents the need for the U.S. to contribute as part of an international process to the ATLAS and CMS detector-wide upgrades that will retain performance and extend the discovery reach for new physics during the HL-LHC running period.

There are few options available for DOE to participate in the HL-LHC upgrade of the ATLAS and CMS detectors at the LHC. DOE could participate through:

Option 1 where the agency continues working together with NSF to support the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades. Each project would be separately managed due to the need to interact closely with the two separate international collaborations building these upgrades. This option best addresses the goals and priorities for HEP at the Energy Frontier outlined by the 2014 P5 strategic plan including the international partnership of the U.S. on the LHC program at CERN.

Option 2 where HEP engages in a partial and independent support for each of the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades. This option would not be the most cost and schedule effective route to a successful upgrade and would complicate coordination with the international process.

Option 3 where HEP does nothing. This option would result in approximately 1,000 DOE-supported researchers on the CMS and ATLAS programs being unable to participate in future LHC runs. This community of researchers has had a major impact on the LHC program worldwide with leadership positions in the collaborations, major technical contributions, and their physics results. Their absence from the continuing program would both slow and reduce the production of scientific results from the LHC. Consequently, it would severely impact the international partnership of the U.S. on the LHC program at CERN and result in HEP unable to maintain a program necessary for mission success.

The upgrade schedule defined by CERN for the LHC and subsequent operation during the HL-LHC period severely constrains the schedule for the upgrades of the ATLAS and CMS detectors.

U.S. participation towards the HL-LHC ATLAS and HL-LHC CMS Detector Upgrades also includes contributions from the NSF. Collaborators from both U.S. ATLAS and U.S. CMS are presently preparing proposals towards a NSF Major Research Equipment and Facility Construction (MREFC) for investment by NSF into the HL-LHC ATLAS and HL-LHC CMS upgrade projects, respectively. The scope of the NSF MREFC projects will focus on areas where university groups, which have been traditionally supported by NSF, have leadership and expertise. HEP will focus on upgrade projects where major national laboratory infrastructure and expertise are needed, critical university collaborations with the laboratories are warranted, and procurement of items require long-lead times. Both the scope of the NSF projects and corresponding funding profiles are therefore constrained by final authorization by the National Science Board on the MREFC projects.

DOE HEP has a Joint Oversight Group (JOG) in place with the NSF to coordinate the two agency partnership for support of common LHC-based experiments. Through the JOG, the understanding has been reached that NSF will pursue a MREFC to support parts of the upgrade to each of the ATLAS and CMS detectors. Both agencies have also discussed initial project scope and costs with the CERN LHC Resources Review Boards (RRB), a forum at which the international experiments regularly report to CERN management and representatives of funding agencies on technical, managerial, and financial matters. Under an understanding through both the JOG and the RRB, HEP would provide about 70% of the overall U.S. project cost and NSF the remaining 30% towards these upgrades.

Environmental, Safety and Health

All work at DOE sites will be conducted under DOE-approved Integrated Safety Management System (ISMS). All facilities will comply with the requirements of the National Environmental Policy Act (NEPA). Based on the nature of the projects, and their planned locations at existing laboratories, impacts to the environment are anticipated to be minimal. For locations in foreign countries, the ES&H policies of the host country will be observed.

Cost Risks

The cost risks are well known because these are upgrades to existing detectors. The cost risk associated with the technically challenging project can be mitigated through a careful technology evaluation program with prototyping and the application of appropriate contingency. Since the projects are contributions to a larger effort, the technical scope of the two projects can be adjusted to keep the project's costs within the stated range should costs begin to escalate.

The scope of the planned contributions to the HL-LHC ATLAS and CMS Detector Upgrade projects between the two agencies, DOE and NSF, will be partitioned and kept distinct to the maximum extent possible with oversight and coordination of the projects conducted through the DOE-NSF JOG. The cost risk associated with any uncertainties from the NSF MREFC process is planned to be mitigated through the CERN LHC RRB by the international ATLAS and CMS collaborations.

Schedule Risks

These are upgrades to existing detectors which could be implemented using the expertise and experience gained from the original construction as well as the intermediate ATLAS and CMS detector upgrade projects presently proceeding on-schedule and expected to be completed in 2019. The upgrades are also closely coordinated with CERN's schedule for LHC operations.

The funding and Critical Decision profiles will also need to be closely coordinated with that of the NSF, which will be a joint partner in the overall projects through a MREFC program as its primary funding mechanism. Both DOE and NSF have successfully conducted joint interagency partnerships of major projects. These projects will follow the lessons learned from those projects.

Safeguards and Security

DOE contributions to experiments would be managed by DOE national laboratories with existent safeguards and security policies and procedures.

There may be International Traffic in Arms Regulations (ITAR) controlled parts of the scientific instrumentation. DOE national laboratories have extensive experience in dealing with the ITAR regulations and no issues are foreseen. A majority of the scientific and technical work is expected to fall under the fundamental research exemption of ITAR.

4. RESOURCE AND SCHEDULE FORECAST

4.1 Cost Forecast

The DOE contribution to the HL-LHC ATLAS and HL-LHC Detector Upgrade projects will each be funded as a Major Item of Equipment (MIE). The cost forecast for each is given for Option 1 in which DOE and NSF form a partnership to build the upgrades. The preliminary DOE Total Project Cost (TPC) range is $125–155 million per project in then-year dollars. The DOE Total Project Cost for both projects will therefore be approximately $250-310 million dollars. The U.S. scope will be divided between the agencies to minimize the dependencies of either agencies scope responsibilities on the scope responsibilities of the other agency. The expected U.S. scope sharing is approximately 70% HEP and 30% NSF. Overall, the contributions by DOE to each of the HL-LHC ATLAS and CMS Detector Upgrades will be approximately 15% of the total international HL-LHC Detector Upgrade cost, which corresponds to the fraction of DOE-supported collaborators on each of the international experiments.

The experience with the existing facilities and successful execution of the initial ATLAS and CMS detector upgrade projects are the best guides to the operations of the experiments and the planned HL-LHC ATLAS and HL-LHC CMS Detector Upgrades, respectively.

4.2 Schedule Forecast

The current estimated dates for major milestones of both the HL-LHC ATLAS and the HL-LHC CMS Detector Upgrades projects are:

Critical Decisions (CD)	*Fiscal Year*
CD-0, Approve Mission Need	*FY 2016*
CD-1, Approve Alternative Selection and Cost Range	*FY 2017*
CD-3a, Approve Purchase of Long-Lead Items	*FY 2018*
CD-2, Approve Performance Baseline	*FY 2018*
CD-3, Approve Start of Construction	*FY 2019*
CD-4, Approve Project Completion	*FY 2026*

4.3 Funding Forecast

The funding profiles shown below for the DOE-supported HL-LHC ATLAS and HL-LHC CMS Detector Upgrade projects, respectively, support the high end of each projects' cost estimate.

DOE: HL-LHC ATLAS Detector Upgrade Project (AY$ Millions)										
Fiscal Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**Total**
Other Project Costs	1.5[a]	5.0[a]	14.0	-	-	-	-	-	-	20.5
Total Equipment Costs	-	-	-	31.5	42.3	26.1	20.1	10.0	4.5	134.5
Total Project Costs	1.5	5.0	14.0	31.5	42.3	26.1	20.1	10.0	4.5	155.0

[a]Funding for Other Project Costs (OPC) in FY 2016 will be redirected from the U.S. ATLAS Operations program. The FY 2017 budget request shows $1.25 million for HL-LHC ATLAS Upgrade OPC. It may be necessary to redirect additional funds from the U.S. ATLAS operations program to support the conceptual design.

DOE: HL-LHC CMS Detector Upgrade Project (AY$ Millions)										
Fiscal Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**Total**
Other Project Costs	1.5[b]	5.0[b]	14.0	2.0	-	-	-	-	-	22.5
Total Equipment Costs	-	-	-	29.5	42.3	26.1	20.1	10.0	4.5	132.5
Total Project Costs	1.5	5.0	14.0	31.5	42.3	26.1	20.1	10.0	4.5	155.0

[b]Funding for Other Project Costs (OPC) in FY 2016 will be redirected from the U.S. CMS Operations program. The FY 2017 budget request shows $1.25 million for HL-LHC CMS Detector Upgrade OPC. It may be necessary to redirect additional funds from the U.S. CMS operations program to support the conceptual design work.

Critical Decision 0, Approve of Mission Need
High Luminosity LHC (HL-LHC) ATLAS and CMS Detector Upgrades

Recommendations:

The undersigned "Do Recommend" (Yes) or "Do Not Recommend" (No) approval of CD-0, for the HL-LHC ATLAS and CMS Detector Upgrades Projects.

Stephen W Meador 4/13/16 Yes ✓ No____
ESAAB Secretariat, Office of Project Assessment Date

4/13/16 Yes ✓ No____
Representative, Office of Budget Date

Yes____ No____
Representative, Safety and Security Policy (ES&H) Date

Earl Hinkle 4/5/2016 Yes ✓ No____
Representative, Safety and Security Policy (Security) Date

4/13/2016 Yes ✓ No____
Representative, Operations Program Management Date
(Facilities and Infrastructure)

Ethel A. Stevens 4/13/2016 Yes ✓ No____
Representative, Non-Proponent SC Program Office Date

4/13/16 Yes ✓ No____
Representative, Non-Proponent Federal Project Director Date

Concurrence:

Patricia M. Dehmer 4/13/2016
Patricia M. Dehmer Date
Deputy Director for Science Programs
Office of Science

Critical Decision 0, Approve of Mission Need
High Luminosity LHC (HL-LHC) ATLAS and CMS Detector Upgrades

Approval:

Based on the information presented in this approval document and at ESAAB Equivalent Review, CD-0, Approve Mission Need, for the HL-LHC ATLAS and CMS Detector Upgrades Projects is approved.

CAMurray 4/13/2016

C. A. Murray, Project Management Executive Date
Director
Office of Science