HIGH LUMINOSITY-LARGE HADRON COLLIDER UPGRADE (HL-LHC) $33,000,000

NSF requests $33.0 million in FY 2020 to begin upgrading components of the A Toroidal LHC ApparatuS (ATLAS) and Compact Muon Solenoid (CMS) detectors to operate at the High Luminosity-Large Hadron Collider (HL-LHC). This is the first year of support for a five-year construction project with a preliminary total project cost of $150.0 million

Appropriated and Requested MREFC Funds for the High Luminosity-Large Hadron Collider (HL-LHC) Upgrade
(Dollars in Millions)

Prior Years	FY 2020 Request	FY 2021 Estimate	FY 2022 Estimate	FY 2023 Estimate	FY 2024 Estimate	Preliminary Project Cost
-	$33.00	$33.00	$33.00	$33.00	$18.00	$150.00

The Large Hadron Collider (LHC) is the world's largest and highest energy particle accelerator. Located near Geneva, Switzerland, and operated by the European Organization for Nuclear Research (CERN), the LHC can accelerate and collide counter-propagating bunches of protons at a total energy of 14 tera-electron volts (TeV). Physicists study the debris from these collisions to learn about the elementary particles and fundamental forces that shape the universe. ATLAS and CMS are two general purpose detectors used by researchers to observe these collisions and analyze their characteristics.

Baseline History
Since 2011, U.S. funding for ATLAS and CMS operations and maintenance (O&M) funding has included investments in advanced research and development (R&D) for investigations into detector modifications that will enable them to function at much higher collision rates following an upgrade to the LHC to increase its luminosity. Each detector group, comprised of researchers from all participating countries, developed a scoping document[1] that described its scientific goals and the technical path forward for operation in the challenging HL-LHC environment.

In 2014, the Particle Physics Project Prioritization Panel (P5) , a subcommittee of the High Energy Physcis Advisory Panel that advises NSF and the U.S. Department of Energy (DOE), recommended U.S. participation in the detector upgrades. In fall 2014, MPS charged a subcommittee of the MPS Advisory Committee (MPS AC) to advise on an appropriate response. The subcommittee, with MPS AC endorsement, recommended NSF provide construction funding at the MREFC level to enable meaningful participation by NSF-supported scientists in the HL-LHC research program.

In November 2015, the NSF Director approved entry of the HL-LHC upgrade to the ATLAS and CMS detectors into the Conceptual Design phase. The principal objectives of this activity were to define a quantitative statement of science requirements, develop a flow-down of the science requirements to a set of technical requirements, define the major technical components, and provide NSF with a top-down estimate of the associated cost, schedule, and risk. Conceptual Design Reviews (CDR) in March-April 2016 established the major functional elements of each detector designated for NSF support and determined that these elements would enable the principal science objectives within the $150.0 million funding envelope defined by NSF in consultation with the MPS AC.

In August 2016, the NSF Director approved entry into the Preliminary Design phase. The principal goals of this phase were to develop a detailed technical description of the scope to be fabricated, the risk-adjusted total project cost for each detector based on bottom-up cost estimates, the corresponding resource-loaded

[1] Atlas: https://cds.cern.ch/record/1502664?ln=en; CMS: http://cds.cern.ch/record/2020886

schedules, year-by-year budget profiles for construction, and plans for managing risk. NSF directed that the total project cost should not exceed $150.0 million, or $75.0 million for each detector. NSF conducted Preliminary Design Reviews (PDR) of CMS and ATLAS, in December 2017 and January 2018 respectively, which established that ATLAS and CMS met the PDR requirements. The review panels expressed confidence that the MREFC scope for each detector upgrade could be accomplished within its individual preliminary $75.0 million MREFC budget cap. NSF subsequently carried out a comprehensive cost analysis that substantiated the basis of estimate for the requested construction budgets.

In July 2018, the NSB authorized the NSF Director to include construction of the High Luminosity upgrades to the ATLAS and CMS detectors in a future Budget Request.

Science Plan

Initial operation of the LHC, and the ATLAS and CMS detectors, enabled the discovery of the Higgs boson in 2012, leading to the 2013 Nobel Prize in Physics. The Higgs mechanism explains how fundamental particles acquire mass. This represents the last major piece in the Standard Model of Particle Physics, which describes all fundamental particles and their interactions. Despite this historic accomplishment, the ATLAS and CMS experiments have only scratched the surface of the ultimate physics potential of the LHC.

There are many open fundamental questions in particle physics. Three key science questions that the HL-LHC program will address are:

- What are the properties of the Higgs boson?
- Are there new particles and interactions beyond those predicted by the Standard Model?
- What is the nature of Dark Matter?

To answer these questions, researchers must compare theoretical predictions with observations of various rare processes, such as those involving the Higgs boson, that could be sensitive indicators of new physical phenomena. Discovering meaningful departures from theoretical predictions will require high precision measurements and the collection of a data sample more than two orders of magnitude larger than the one used for the Higgs discovery in 2012. To accomplish this, CERN plans to upgrade the accelerator, which will be renamed the High Luminosity-LHC, to deliver the high intensity proton beams required. In parallel, NSF proposes to fund the development of critical components of the ATLAS and CMS detectors that will allow them to record and analyze the torrent of data to be produced. The accelerator enhancements and the detector upgrades will be installed and commissioned during 2024-2026.

More than 50 funding agencies worldwide will contribute various components of the upgraded detectors, including significant contributions by DOE. NSF is working closely with DOE to coordinate development and design activities, as well as operational aspects of their mutual involvement in the operation of the ATLAS and CMS detectors. The HL-LHC will commence 10-years of operation in mid-2026 to produce more than 10-times the data collected by LHC operation through 2024.

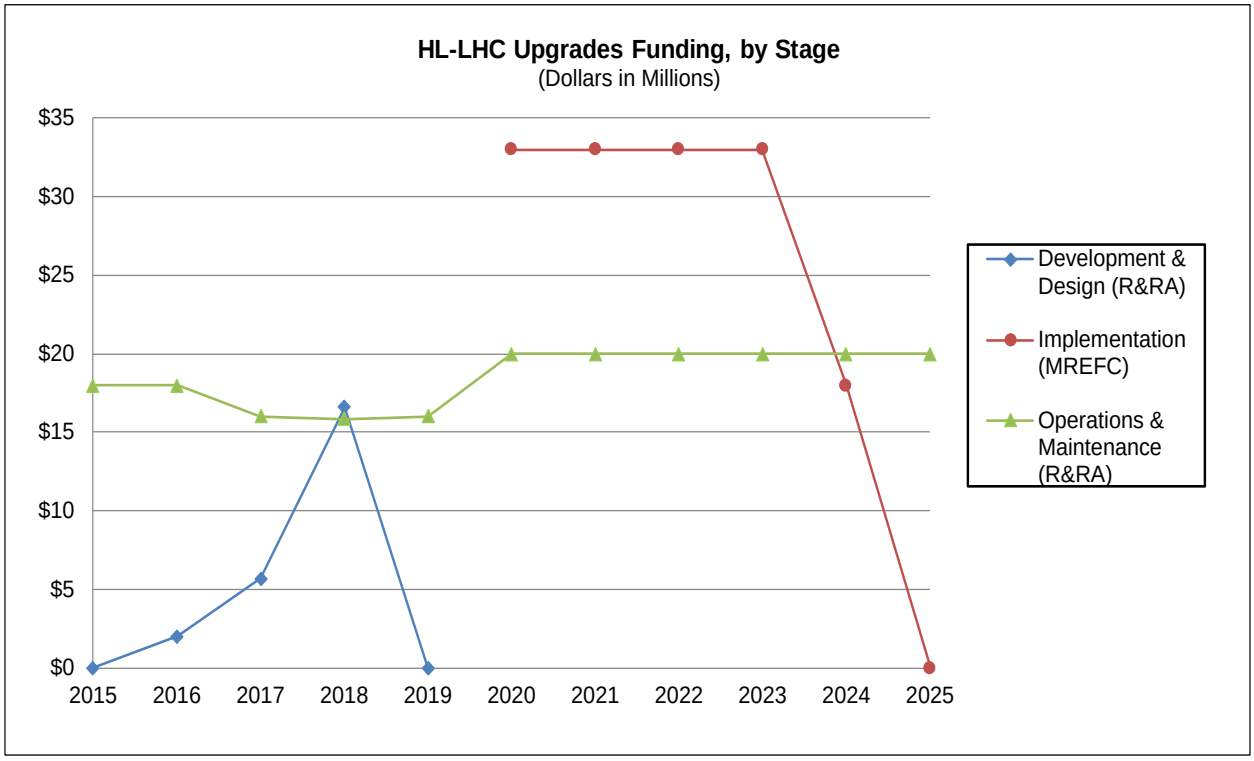
Total Funding Requirements for HL-LHC Upgrades

(Dollars in Millions)

	Prior Years	FY 2018 Actual	FY 2019 (TBD)	FY 2020 Request	ESTIMATES FY 2021	FY 2022	FY 2023	FY 2024	FY 2025
R&RA:									
Development & Design[1]	$7.71	$16.60	-	-	-	-	-	-	-
Operations & Maintenance[2]		15.86	-	20.00	20.00	20.00	20.00	20.00	20.00
Subtotal, R&RA	$7.71	$32.46	-	$20.00	$20.00	$20.00	$20.00	$20.00	$20.00
MREFC:									
Implementation	-	-	-	33.00	33.00	33.00	33.00	18.00	-
Subtotal, MREFC	-	-	-	$33.00	$33.00	$33.00	$33.00	$18.00	-
TOTAL REQUIREMENTS	**$7.71**	**$32.46**	**-**	**$53.00**	**$53.00**	**$53.00**	**$53.00**	**$38.00**	**$20.00**

[1] The FY 2018 Actual reflects $7.50 million of forward funding for FY 2019 and FY 2020 HL-LHC development and design. No additional funds are expected in these years.

[2] O&M funding represents operations support for the current LHC facility and is forecast to remain constant during the HL-LHC upgrade. Installation, integration, and system testing of the upgraded detectors will be coordinated by CERN during 2024-2026. NSF's share of installation and commissioning costs is estimated at $5.0 million per detector, which will be funded from the FY 2024-2026 O&M budgets.



Management and Oversight

- NSF Structure: NSF oversight is handled by a program officer in the MPS Division of Physics (PHY). Cross-foundation coordination is provided by an integrated project team (IPT) that includes staff from the Office of the Director, Office of the General Counsel, Office of Legislative and Public Affairs, Office of the Assistant Director for MPS, OISE, EHR, and BFA. Within BFA, the Large Facilities Office and the Division of Acquisition and Cooperative Support provide advice to program staff and assists with agency oversight and assurance. The NSF program officer works closely with PHY

colleagues overseeing the Experimental Particle Physics research program at NSF, and with counterparts in the DOE Office of High Energy Physics. Interagency coordination is accomplished through a Joint Oversight Group (JOG), which meets semi-annually. The framework for joint DOE/NSF oversight of the U.S.-led portion of the international ATLAS and CMS collaborations has a successful history spanning nearly two decades. It is based on an initial interagency memorandum of understanding implemented in December 1999 and superseded in March 2018 to encompass HL-LHC activities.

- External Structure: Columbia University (ATLAS) and Cornell University (CMS) will be the primary MREFC awardee institutions. NSF-funded principal investigators at Columbia and Cornell will be responsible for accomplishing the NSF-designated scope. NSF and DOE funded activities, which together form the U.S. collaboration for ATLAS and CMS, will be coordinated through the JOG as described above. The U.S. collaboration will coordinate with the international ATLAS and CMS project leadership to accomplish the entire upgrade program. The NSF construction scope for ATLAS and CMS was selected, at the outset of Conceptual Design, to be minimally coupled to other construction activities of DOE or international partners so that NSF's construction can be executed as two relatively independent projects within the overall scope of upgrade activities. NSF currently receives monthly technical status reports and quarterly financial reports of development and design activity and will receive monthly financial and technical status reports throughout construction. Revisions to the scope, budget, and schedule baselines will be reported to NSF, and revisions exceeding thresholds to be defined in the cooperative agreements for construction will require prior NSF approval.
- Interaction with CERN: In May 2015, DOE, NSF, and CERN executed a Cooperation Agreement concerning scientific and technical cooperation in nuclear and particle physics. The Cooperation Agreement establishes the framework under which DOE, NSF, and their awardees, as well as DOE national laboratories, will participate in the particle physics programs in the international ATLAS and CMS detector collaborations (under the auspices of CERN) in the era of the HL-LHC. Subject to availability of appropriated funds, NSF's total contributions to the HL-LHC upgrade program will be specified and incorporated under separate implementing arrangements in the form of addenda to the 2015 Cooperation Agreement. The CERN LHC Resources Review Boards (separate boards for ATLAS and CMS) are composed of representatives from each participating funding agency. The Boards monitor and oversee resource-related matters as defined by the framework for participation in each experiment. NSF is a full member of these LHC Resources Review Boards. The Boards meet semi-annually to approve all LHC upgrade planning at the international level.

Reviews

- Conceptual Design Reviews: March 2016 (ATLAS); March and April 2016 (CMS).
- Preliminary Design Reviews: January 2018 (ATLAS); December 2017 (CMS).
- Review of the Operations and Maintenance Plans of ATLAS and CMS for 2017-2021 (whose scope includes development and design activities for the detector upgrades): July 2016 (ATLAS); July 2016 (CMS).
- Department of Energy (DOE) Critical Decision 1 (CD-1) reviews: June 2018 (CMS); July 2018 (ATLAS). CD-1 approval marks the completion of the project definition phase and the conceptual design.
- Major subsystems of the combined international effort were scientifically and technically reviewed by the CERN LHC Committee (LHCC), an international committee of technical experts, followed by a cost and schedule review by the CERN Upgrade Cost Group, an international committee of technical and financial experts, which reported to the LHCC (July 2017-April 2018).

Project Status

PDR verified that all aspects of the technical scope are well defined. The flow-down from science to engineering requirements is sound and the lowest level requirements appear to be complete. Designs are

capable of meeting performance requirements and are sufficiently mature that their risk-adjusted budgets may be confidently estimated. The Project Execution Plan (PEP) for each detector upgrade defines the construction responsibilities of the individual PIs and the awardee and subawardee university research groups. Each PEP documents the schedule and labor needed to accomplish these tasks. Each project has developed a credible resource-loaded schedule, defining the integration of these tasks and the logical sequence of work to be done.

During the Final Design phase, ATLAS and CMS will complete prototyping and preproduction testing of detector elements and electronic components. The PDR determined that the remaining engineering challenges are clearly defined and that the ATLAS and CMS development teams can meet them.

ATLAS and CMS will complete preparatory planning and enabling R&D with the goal of commencing construction in April 2020. NSF plans to hold Final Design Reviews of ATLAS and CMS around September 2019. In parallel, NSF will carry out a Cost Analysis informed by an Independent Cost Estimate review of the upgrades to confirm the validity of the construction-ready cost estimate for each detector.

Cost and Schedule

Funding for development and design was accomplished by redirecting $2.0 million per year from the LHC O&M budget in FY 2017-2019 and augmenting this amount with funding from the Division of Physics, including $7.50 million of forward funding from FY 2018 funds for FY 2019 and FY2020.

The planned April 2020 construction start date is dictated by the need to complete fabrication and delivery to CERN to meet the international integration schedule for 2024-2026. A significant delay could result in the transfer of critical NSF-funded scope to other international partners for accomplishment, resulting in lost leadership opportunities for U.S. scientists. NSF's contributions to the ATLAS and CMS upgrades represent about six percent of the international detector upgrade program.

The MREFC project will be completed when the NSF-funded apparatus is delivered and passes component performance testing at CERN. Installation, integration, and system testing will be coordinated by CERN during 2024-2026. NSF's share of installation and commissioning costs is estimated at $5.0 million per detector, which will be funded from the FY 2024-2026 O&M budgets. The annual O&M cost is forecast to remain constant during and following the HL-LHC upgrade installation.

Risks

Technical Risk: Technical designs are sufficiently mature to credibly support estimates of the costs to complete development and industrialization, and of construction. Remaining technical decisions during the Final Design stage have credibly bounded cost and schedule impacts. There are multiple alternatives for dealing with the remaining design uncertainties.

Deployment Risk: The MREFC project concludes with delivery and verification of subcomponent operability at CERN. CERN has overall responsibility for assembly, integration, and commissioning of the upgraded detectors, integrating the contributions from more than 40 different countries. While a slip in the CERN schedule will delay scientific research, it will not increase the cost of the NSF-funded construction. A significant delay may place schedule demands on NSF's O&M beyond 2026.

Management Risk: The PDRs established that the ATLAS and CMS management teams are well-qualified. Their organizational structures and delegations of responsibility are appropriate for planning and construction. After reviewing evidence of high-quality cost estimating processes (as defined in the GAO Cost Estimating and Assessment Guide[2]), the PDR review panel reports expressed confidence that each

[2] www.gao.gov/new.items/d093sp.pdf

upgrade can be accomplished within its estimated TPC of $75.0 million. The construction schedules for each upgrade have realistic durations and are based on sound assumptions and methods. Conservative estimates of the time needed to accomplish critical tasks significantly mitigate the risk of incurring overall delay in completing construction, although there are opportunities for continued optimization of schedule risk that will be pursued during Final Design.

Partnership Risk: This activity supported through DOE and NSF research grants to universities, which creates a partnership risk where a potential shortfall in available research funding to one agency could impair the construction plans of the other. NSF and DOE plan to work closely in the lead-up to construction to regularly monitor and coordinate risk planning.

Disposal Costs: CERN's policy is to dispose of all irradiated detector components when they are no longer used in the detectors. Consequently, there are no anticipated costs to NSF at the end of operation.

Future Operations Costs

An additional agreement between NSF, DOE, and CERN ("Experiments Protocol II"), signed in December 2015, documents the responsibilities of U.S. participants to provide normal maintenance and operation of detector subsystems and components provided by NSF and DOE. Future MOUs with CERN will describe the distribution of tasks and other responsibilities for all participating institutions, including those supported by NSF, as well as the organizational, managerial, and financial guidelines to be followed by each detector collaboration. NSF anticipates providing approximately three percent of the total operation cost of the ATLAS and CMS detectors during HL-LHC operation (as it does today). This proportion is based on the number of NSF-supported scientists in each collaboration.

Data handling and computing costs are not yet established. A 10-fold increase in data rates would have dramatic consequences if dealt with using currently available technology. A well-orchestrated global effort is underway, progressing in parallel with the HL-LHC detector upgrades, to meet these needs. ATLAS and CMS are coordinating their efforts within this framework to seek common solutions. This improved coordination extends to the U.S. funding agencies, other funding agencies, and CERN. These efforts will coalesce into a planned 2020 HL-LHC Computing Technical Design Report, which will lay the foundation for a computing and data management system that will meet the requirements of the HL-LHC in 2026. NSF's support for the new system will come from within the approximately $10.0 million per year operational support it plans to provide each detector for O&M. In addition, NSF recently made a five-year, $25.0 million award to a consortium of 17 universities led by Princeton University to establish a software institute as a first step toward addressing the Big Data and computing challenges imposed by the data demands of the upgraded detectors.