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

The FY 2021 Request for the HL-LHC Upgrade is $33.0 million. This funding will support ongoing component upgrades 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 second year of a five-year construction program that is expected to begin in FY 2020. See the Baseline History section below for more details on the approval timeline.

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

FY 2020	FY 2021 Request	FY 2022 Estimate	FY 2023 Estimate	FY 2024 Estimate	FY 2025 Estimate	Preliminary Total Project Cost[1]
$33.00	$33.00	$36.00	$33.00	$18.00	-	$153.00

[1] Final number is pending NSB authorization, expected February 4, 2020.

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. 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. Detailed discussion of the current operations of LHC funded by NSF may be found in the Facilities Chapter.

Baseline History

Since 2011, U.S. funding for ATLAS and CMS O&M has included investments in advanced research and development (R&D) for investigations into detector modifications. These modifications will enable them to function at much higher collision rates following an upgrade to the LHC to increase its luminosity. The ATLAS and CMS groups, comprised of researchers from all participating countries, each 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 Physics 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

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

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 estimated $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 (TPC) for each detector based on bottom-up cost estimates, the corresponding resource-loaded schedules, year-by-year budget profiles for construction, and plans for managing risk. NSF directed that the initial estimated TPC 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 both projects 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 target. NSF subsequently carried out a comprehensive cost analysis that supported the basis of estimate for the requested construction budgets.

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

Final Design Reviews (FDRs) held in September 2019 validated the construction-readiness of the upgrade plans. The FDRs established that the potential impacts of remaining pre-construction design and development are adequately bounded within the risk-adjusted budget of each collaboration. In this review process, the CMS budget was adjusted upward by $3.0 million to cover possible increased costs related to critical components. The NSF director will seek NSB's authorization to begin construction in FY 2020, with a five-year MREFC award totaling $153.0 million.

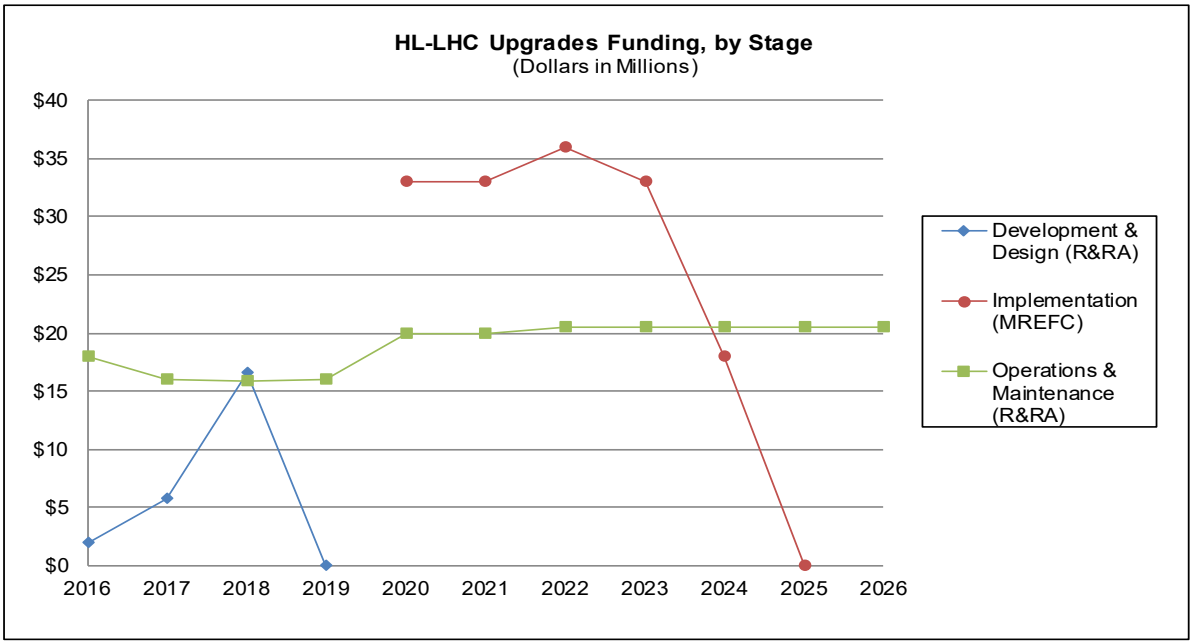
Total Funding Requirements for HL-LHC Upgrade

(Dollars in Millions)

	Cumulative Prior Years	FY 2019 Actual	FY 2020 Request	FY 2021 Request	ESTIMATES[1] FY 2022	FY 2023	FY 2024	FY 2025	FY 2026
R&RA:									
Development & Design	$24.31	-	-	-	-	-	-	-	-
Operations & Maintenance[2]		16.00	20.00	20.00	20.50	20.50	20.50	20.50	20.50
Subtotal, R&RA	$24.31	$16.00	$20.00	$20.00	$20.50	$20.50	$20.50	$20.50	$20.50
MREFC:									
Implementation	-	-	33.00	33.00	36.00	33.00	18.00	-	-
Subtotal, MREFC	-	-	$33.00	$33.00	$36.00	$33.00	$18.00	-	-
TOTAL REQUIREMENTS	**$24.31**	**$16.00**	**$53.00**	**$53.00**	**$56.50**	**$53.50**	**$38.50**	**$20.50**	**$20.50**

[1] Outyear funding estimates are for planning purposes only. The current cooperative agreements end in December 2021 (CMS) and January 2022 (ATLAS).

[2] O&M funding represents operations support for the current LHC facility and is forecast to remain constant at a level of $20.50 million during the HL-LHC upgrade. Installation, integration, and system testing of the upgraded detectors will be coordinated by CERN during 2025-2027. NSF's share of installation and commissioning costs is estimated at $5.0 million per detector, which will be funded from the FY 2025-2027 O&M budgets.



HL-LHC 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 construction 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 are expected to be installed and commissioned from 2025 through mid-2027.

More than 45 funding agencies worldwide are contributing various components of the upgraded detectors; NSF and DOE each anticipate significant contributions, and together fund the U.S. HL-LHC program that is responsive to the P5 recommendation. NSF investments in the upgrades will enable university-based U.S. scientists and students to participate in the HL-LHC experimental program. NSF is working closely with DOE to coordinate development and design activities and to jointly oversee each detector's operation. HL-LHC will commence ten years of operation in mid-2027 to produce more than ten times the data collected by LHC operation through 2024.

Management and Oversight

NSF Structure: NSF oversight is handled by a program officer in PHY. Cross-foundation coordination is provided by an integrated project team that includes staff from MPS, BFA, EHR, OISE, the Office of the Director, the Office of the General Counsel, and the Office of Legislative and Public Affairs. Within BFA, the Large Facilities Office and the Division of Acquisition and Cooperative Support provide advice to program staff and assist with agency oversight and assurance. The MPS Facilities team and NSF's Chief Officer for Research Facilities also provides high-level guidance and oversight support for the project. 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 two decades. It is based on an initial interagency memorandum of understanding (MOU) implemented in December 1999 and superseded in March 2018 to encompass HL-LHC activities.

External Structure: 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, are coordinated through the JOG as described above. The U.S. collaborations 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 financial and technical status reports on pre-construction planning activities. Revisions to the scope, budget, and schedule baselines will be reported to NSF, and revisions exceeding thresholds 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, 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

- CDR: March 2016 (ATLAS); March and April 2016 (CMS).
- PDR: January 2018 (ATLAS); December 2017 (CMS).
- Review of the O&M Plans of ATLAS and CMS for CY 2017-2021 (whose scope includes development and design activities for the detector upgrades): July 2016 (ATLAS); July 2016 (CMS).
- CERN international committee reviews: 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).
- FDR: September 2019 (ATLAS and CMS).
- Full Life-cycle Cost Reviews: NSF held reviews of the cost impacts of the MREFC upgrades on the LHC operations program in October 2019.

Project Status

The ATLAS and CMS FDRs established that each detector collaboration had completed all NSF-mandated pre-construction preparation needed to enable construction to commence in April 2020. The FDR panels considered each of the construction readiness criteria in NSF's Major Facilities Guide and advised NSF on whether they had been satisfied. The FDR panels also evaluated the sufficiency of each collaboration's response to the recommendations from prior reviews and offered suggestions to NSF on areas to follow closely during construction. NSF and the NSB are conducting additional assessments to assure readiness for an April 2020 construction start. NSF's Large Facilities Office is leading an Independent Cost Estimate of each project as part of the overall cost assessment process carried out by BFA. These will be completed and satisfactorily reconciled prior to awarding construction funds in FY 2020.

Cost and Schedule

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 CY 2025-2027. 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 verification of delivery in good condition at CERN. Installation, integration, and system testing will be coordinated by CERN during CY 2025-2027. NSF's share of installation and commissioning costs is estimated at about $5.0 million per detector, which will be funded from the FY 2025-FY 2027 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, the total project cost of the NSF-funded construction projects is not anticipated to increase. A significant delay may increase demands on NSF's O&M beyond 2027.

Management Risk: The FDRs established that the ATLAS and CMS management teams are well-qualified and well prepared to undertake the proposed construction activities, with appropriate organizational structures and delegations of responsibility. The review committees reported each team's development of cost and schedule estimates was based on sound assumptions and methods that are consistent with best practices defined by the Government Accountability Office in the Cost Estimating and Schedule

Assessment guides. The FDR panels also expressed confidence that each upgrade can be accomplished within its estimated TPC, after adjusting the CMS estimate upward by $3.0 million to cover possible increased costs related to critical components. The ATLAS and CMS Project Execution Plans include detailed risk management considerations and mitigation strategies. The risk impacts of remaining development uncertainties, prior to the start of construction, are reasonably bounded within the proposed cost, scope, and schedule estimates.

Partnership Risk: The NSF scope for the detector upgrades relies on the successful and timely completion of development testing by international partners of some key components, such as radiation-tolerant custom electronic circuits. A second partnership risk is that the detector fabrication activities within the NSF scope rely in part on DOE and NSF research grants to universities. Faculty, post-docs, and graduate students will participate in the management, testing, characterization, and software development of detector components fabricated by engineers and technicians. While the engineering and technical labor is funded through the MREFC awards, the faculty, post-docs, and graduate students are supported by research grants from DOE and NSF to universities and colleges. Risks and contingency budgets were refined through the FDR process to assure NSF that partnership risks are confidently addressed.

Disposal Costs: CERN's policy is to dispose of all detector components when they are no longer used in the detectors. NSF will be responsible only for covering its share of the demolition costs to remove each detector from its underground operating location and transport it to the surface for disposal by CERN. At the Full Life-Cycle Cost Reviews each detector estimated these costs at approximately $1-2 million (not escalated).

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. NSF's external reviews of the impacts of the HL upgrades on future operating costs indicated that these operating cost projections are reasonable and are based on realistic assumptions.

A well-orchestrated global effort is underway, progressing in parallel with the HL-LHC detector upgrades, to meet the challenges of computing in the HL era. 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. NSF conducted external reviews (the Full Life-Cycle Cost Reviews mentioned earlier) of the impacts of future computing needs on the operations program. The reviewers expressed confidence that the multiple software research programs now underway to address these challenges are likely to provide affordable solutions. Many of the R&D tasks underway are promising, and only a subset needs to be successful to meet the needs of the HL operating program.