HIGH LUMINOSITY-LARGE HADRON COLLIDER UPGRADE (HL-LHC) $0

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

	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024 Request	FY 2025 Request	Total Project
Previous Authorized Total Project Cost	$33.00	$33.00	$36.00	$33.00	$18.00	-	$153.00
Rebaseline Impact[1]	-	-	-	-	20.00	-	20.00
Revised Total Project Cost Estimate	**$33.00**	**$33.00**	**$36.00**	**$33.00**	**$38.00**	**-**	**$173.00**

[1] Amount informed by 2023 Rebaseline review, which included a review of cost and schedule.

Brief Description

The Large Hadron Collider is the world's largest and highest-energy particle accelerator. Located near Geneva, Switzerland and operated by the European Organization for Nuclear Research (CERN), LHC is designed to accelerate and collide counter-propagating bunches of protons at a total energy of up to 14 TeV (one TeV=10^{12} electron volts). Physicists study the debris from these collisions to learn about the elementary particles and fundamental forces that shape the universe. U.S. involvement in LHC is jointly supported and overseen by NSF and the Department of Energy (DOE) and is primarily focused on supporting research, upgrades, and operations and maintenance (O&M) at two general purpose detectors: "A Toroidal LHC ApparatuS" (ATLAS) and "Compact Muon Solenoid" (CMS). HL-LHC is an enhancement to the accelerator that will increase the proton collision rate (known as "luminosity") by a factor of about 5 to 7. The upgrades funded by this request are modifications to the ATLAS and CMS detectors that will enable them to operate at the higher collision rate and with greater measurement precision. NSF's HL-LHC upgrade program represents about 7 percent of the global high luminosity upgrade effort at LHC, which is being supported by 60 funding agencies internationally.[1]

NSF's FY 2025 Request for HL-LHC is zero since the FY 2024 Request accurately anticipated the successful re-baseline review and resulting estimate of an updated total program cost (TPC) of $173.0 million. In completing the re-baseline review during the spring of 2023, NSF worked closely with the management of the ATLAS and CMS detector upgrade projects to more fully understand the schedule delays and increased costs that had been incurred. These resulted from the direct and indirect impacts of COVID-19, historically high inflation, CERN LHC schedule revisions, supply-chain delays, and the Russian attack on Ukraine (both Russia and Ukraine participate in LHC research and detector upgrade activities, and in June 2022 the CERN Council announced its intent to end cooperation with Belarus and Russia in June and December 2024, respectively). These factors were the main considerations in the 2023 re-baseline reviews conducted by external expert panels.

Through their detailed review, the panels determined that the re-baselined project plans comply with

[1]U.S. DOE is among the other agencies supporting the overall HL upgrade effort, including the upgrade to the accelerator, while NSF supports only the upgrades to the ATLAS and CMS detectors. The scope of DOE-supported activities is independent of the NSF-supported scope, though some links exist at the level of university-based efforts. NSF and DOE coordinated development and design efforts in preparation for construction of the HL upgrades and will continue joint oversight of the U.S. components of the ATLAS and CMS O&M programs through the HL upgrades and subsequent operations; see the Governance Structure and Partnerships section below for details.

NSF's re-baselining guidance as well as the detailed requirements of the NSF Research Infrastructure Guide and the best practices in GAO's Cost Estimating and Schedule guides. The panels also concluded that there is high confidence that the new TPC will allow for the successful completion of both projects within the total that includes the FY 2024 request.

Baseline History

Following an agreement among NSF, DOE, and CERN ("Experiments Protocol I"), signed in December 1997, NSF began support for construction of ATLAS and CMS detector elements and software development in 1998. NSF has subsequently supported ongoing O&M,[2] as well as a previous smaller-scale upgrade to each detector. Since 2011, U.S. funding for ATLAS and CMS O&M has included investments in advanced R&D for investigations into detector modifications that enable the detectors to function at much higher collision rates in conjunction with an upgrade to increase the luminosity of LHC. The ATLAS and CMS groups, consisting of researchers from all participating countries, each developed scoping documents describing their scientific goals and the technical paths forward for operation in the challenging high-luminosity environment planned for HL-LHC.

In 2014, the Particle Physics Project Prioritization Panel (P5), a subcommittee of the High Energy Physics Advisory Panel that advises NSF and DOE, recommended U.S. participation in the detector upgrades. In fall 2014, MPS charged a subcommittee of its Advisory Committee (MPS AC) to advise on an appropriate response. The subcommittee, with MPS AC endorsement, recommended that NSF provide construction funding at the major facility level to enable meaningful participation by NSF-supported scientists in the HL-LHC research program. A $150.0 million funding target was defined by NSF in consultation with the MPS AC.

In July 2018, after completing the requirements of the major facility Preliminary Design phase, the NSF Director included construction of the High Luminosity upgrades to the ATLAS and CMS detectors in the Budget Request. Funding to begin construction was provided in the FY 2020 MREFC appropriation, and separate construction awards to Columbia University and Cornell University (for ATLAS and CMS projects, respectively) were issued, totaling $153.0 million (adjusted upward by $3.0 million in the Final Design Review process).

Project Status

Each project is currently (as of November 2023) approximately 40 percent complete. The re-baseline reviews described above resulted in revised schedules with both projects finishing in FY 2027, before the CERN need-by date.

Summary of COVID-19 Impacts

The estimated financial impact of the COVID-19 pandemic on the NSF components of the ATLAS and CMS detectors is $20.0 million and is captured within the FY 2023 re-baseline. In January 2022, reacting to pandemic impacts on the overall upgrade schedule and the individual funding agencies participating in the upgrades, CERN announced a one-year delay to the start of installation of the HL-LHC accelerator and detector components, moving the date from January 2025 to January 2026. CERN

[2] Oversight of the U.S. component of the ATLAS and CMS O&M programs is jointly conducted by NSF and DOE. See the Governance Structure and Partnerships section below.

additionally announced an extension in the installation period to three full years – through the end of calendar year 2028 (rather than the two and one-half years that had been previously planned) to allow these activities to be completed.

Meeting Intellectual Community Needs

Initial operation of 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. Despite this historic accomplishment, the ATLAS and CMS experiments have only scratched the surface of the ultimate physics potential of 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 is upgrading the accelerator, which will be renamed the High Luminosity-LHC, to deliver the required high intensity proton beams. CERN plans to commence ten years of operation of HL-LHC in 2029. Over the subsequent decade, HL-LHC is expected to produce more than 10 times the data collected by LHC operation through 2025 (a hundred-fold increase relative to the data set that was used to confirm the 2012 Higgs discovery).

In parallel with the accelerator upgrade, NSF is funding 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. NSF contributions primarily fund radiation-hard electronics that increase the spatial granularity of calorimeter and muon detectors, expansion of the charged-particle tracking close to the beam direction in the CMS detector, and major improvements to the fast-decision-making electronics that trigger each detector to select and record interesting, rare events.

Currently, more than 1,200 U.S. researchers participate in the ATLAS and CMS collaborations, including more than 100 post-doctoral fellows and more than 400 students, of whom about half are undergraduates. The U.S. researchers comprise about 20 percent of the total membership of the ATLAS and CMS collaborations. NSF supports about 20 percent of the U.S. ATLAS and CMS contingents.

Governance Structure and Partnerships

NSF Governance Structure

NSF oversight is handled by a program officer in the Division of Physics (PHY). Cross-foundation coordination is provided by an Integrated Project Team that includes staff from MPS, BFA, EDU, OISE, the Office of the General Counsel, and the Office of Legislative and Public Affairs. Within BFA, the Research Infrastructure Office (RIO) 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 provide 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 at least 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 more than two decades. It is based on an interagency Memorandum of Understanding (MOU) that was initially implemented in December 1999 and that was replaced by a new MOU in March 2018 to encompass HL-LHC activities.

External Governance Structure

NSF-funded principal investigators at Columbia University and Cornell University are responsible for managing and accomplishing the NSF-designated scope of the ATLAS and CMS projects. 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 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, which meet semi-annually to oversee and approve all LHC upgrade plans and major decisions at the international level.

Partnerships and Other Funding Sources

More than 60 funding agencies worldwide are contributing various components of the upgraded detectors. NSF investments in the upgrades enable university-based U.S. scientists and students to participate in the HL-LHC experimental program, which currently has over 8,000 participants worldwide. NSF is working closely with DOE to coordinate construction activities and to jointly oversee each detector's operation.

In May 2015, DOE, NSF, and CERN executed a cooperation agreement concerning scientific and technical cooperation in nuclear and particle physics. The cooperation agreement established 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 HL-LHC. Subject to availability of appropriated funds, NSF's total contributions to the HL-LHC detector upgrade program are specified and incorporated under separate implementing arrangements in the form of addenda to the 2015 cooperation agreement.

Cost and Schedule

Commencement of NSF-funded construction in April 2020 was considered critical to enable recipient U.S. universities to undertake timely fabrication and delivery of components to CERN to meet the international integration schedule. A significant delay could have resulted in the transfer of NSF-funded scope to other international partners, resulting in lost opportunities for U.S. scientists.

The major facility construction projects will be completed when the NSF-funded components for both detectors are delivered and verified at CERN to be in good working order. NSF will support the subsequent installation, integration, and system testing of the NSF-funded components at CERN through awards to U.S. ATLAS and U.S. CMS collaborations for detector O&M. This work is currently planned to occur during CY 2026-2028. NSF's share of installation and commissioning costs was estimated before the pandemic at about $5.0 million per detector and reconfirmed in reviews NSF held in July 2021. The annual O&M cost is forecast to remain constant during and following the HL-LHC Detector Upgrade installation.

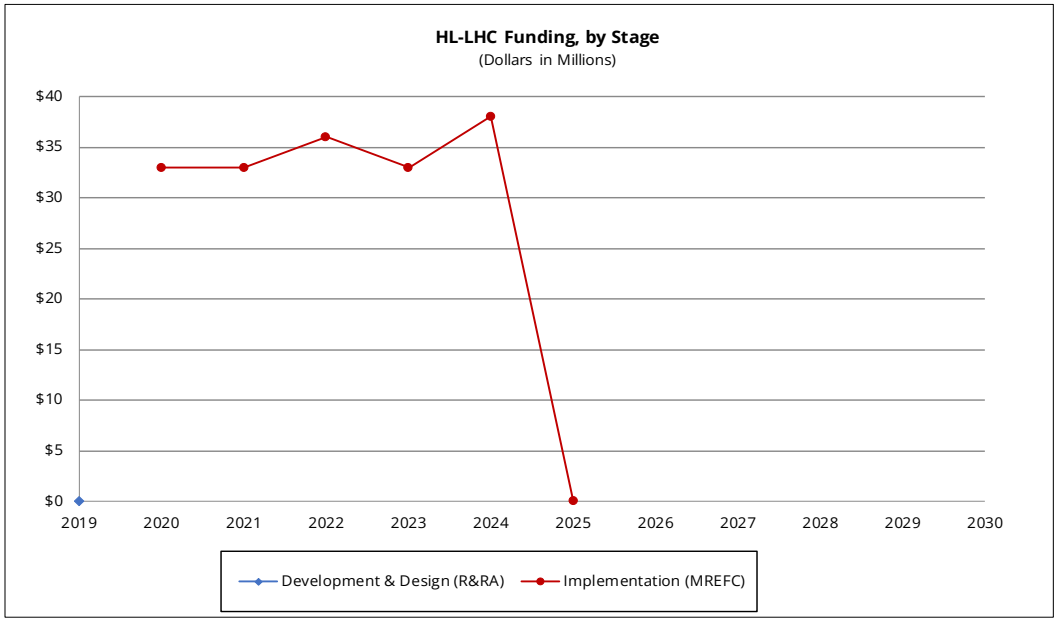
Total Funding Requirements for HL-LHC Upgrade
(Dollars in Millions)

	Prior Years	FY 2023	FY 2024 Request	FY 2025 Request	ESTIMATES[1] FY 2026	FY 2027	FY 2028	FY 2029	FY 2030
R&RA:									
Development & Design	$24.31	-	-	-	-	-	-	-	-
Operations & Maintenance[2]		-	-	-	-	-	TBD	TBD	TBD
Subtotal, R&RA	$24.31	-	-	-	-	-	-	-	-
MREFC:									
Implementation[3]	102.00	33.00	38.00	-	-	-	-	-	-
Subtotal, MREFC	$102.00	$33.00	$38.00	-	-	-	-	-	-
TOTAL REQUIREMENTS	**$126.31**	**$33.00**	**$38.00**	**-**	**-**	**-**	**TBD**	**TBD**	**TBD**

[1] Outyear estimates are for planning purposes only.

[2] FY 2028 and beyond are TBD because possible CERN schedule delays may move the operations phase of HL-LHC past this reporting window.

[3] FY 2024 amount informed by 2023 Re-baseline review, which included a review of cost and schedule.



Future Operations Costs

An additional agreement among NSF, DOE, and CERN ("Experiments Protocol II"), signed in December 2015, follows on from the more general cooperation agreement signed in May 2015; it documents the

responsibilities of U.S. participants to provide normal O&M 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 operations 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 projections are reasonable and are based on realistic assumptions. These projections are regularly revisited during the period of construction to incorporate evolving understanding of the impacts of the pandemic and other events on future operation.

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 in areas of mutual interest. The coordination framework extends across the U.S. ATLAS and U.S. CMS collaborations, the U.S. funding agencies, other national funding agencies, and CERN. In July 2021, NSF conducted reviews of the software and computing R&D efforts that are underway to develop tools and methods that will satisfy future computing needs during HL-LHC operation. The reviewers expressed confidence that the multiple ongoing software research programs are likely to provide affordable solutions within the flat computing budgets that are planned (by NSF, DOE, and funding agencies in other countries). Many of the R&D tasks now underway are promising, and only a subset needs to be successful to meet the needs of the HL operating program.

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 collaboration estimated these costs at approximately $1.0-2.0 million (not escalated).

Reviews

- Conceptual Design Reviews (2016), Preliminary Design Reviews (2017-2018) and Final Design Reviews (2019) with external review panels were carried out in accordance with the requirements of NSF's Major Facilities Guide (subsequently renamed to the Research Infrastructure Guide), with panel reports favorable to the continuation of the program as designs matured.
- 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) were held in July 2016.
- 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 that reported to the LHCC (July 2017-April 2018).
- Full Life-cycle Cost Reviews: NSF held reviews of the cost impacts of the HL upgrades on the LHC operations program in October 2019.
- NSF held external reviews of ATLAS and CMS installation plans and software and computing R&D

projects in July 2021 to assess the stability of the planned scope, the forecast budget needs and schedule requirements, and the risk projections for these activities. The reviews indicated that these activities are well-planned and appropriately budgeted. Impacts from possible future revisions by CERN to the LHC run schedule are estimated to have minimal budget impact.

- Reviews of ATLAS and CMS HL upgrade activities took place in August 2021 to examine the current technical, financial, schedule, and risk status of each project and the current assessments of total pandemic impacts.
- At the end of January 2022, NSF and DOE conducted joint reviews of ATLAS and CMS Operations. The reviews included an assessment of the status and plans for software and computing R&D that will facilitate efficient and cost-effective processing of HL-LHC data. The reviews provided assurance that ATLAS and CMS will have in place the data processing capabilities needed to analyze HL-LHC data.
- Re-baselining reviews of the CMS and ATLAS detector upgrades were held in March and April 2023. The external reviews and NSF's internal cost assessment of the budget and schedule changes requested now confirm the MREFC funding needed in FY 2024 and that no additional funding is required in FY 2025.

Risks

Technical Risk

Technical designs were sufficiently mature at the start of construction to credibly support estimates of the costs to complete construction. Cost and schedule impacts due to technical risks are credibly bounded. There are multiple alternatives for dealing with the known production uncertainties, although the unanticipated impacts of the pandemic have introduced supply chain issues and substantially delayed access to radiation testing facilities needed to verify design performance. Progress to date, such as completion and testing of prototypes, pre-production fabrication of limited quantities of detector components, and system integration tests have retired many technical risks.

Deployment Risk

The MREFC-supported construction projects conclude with delivery and verification of subcomponent operability at CERN. CERN has overall responsibility for coordinating the assembly, integration, and commissioning of the upgraded detectors, integrating the contributions from more than 40 different countries to each detector. While a slip in the CERN schedule for installation will delay scientific research, the TPC of the NSF-funded construction projects is not anticipated to increase due to the expanded time interval between delivery of those elements to CERN and CERN's recently revised start of installation (which NSF supports through its funding of ATLAS and CMS O&M programs). CERN has delayed the original installation schedule due to pandemic impacts and other factors. This new schedule was considered during the re-baseline review of 2023, which concluded that the NSF deliverables will arrive in time at CERN. If any additional factors result in changes to the installation and commissioning requirements and methods, the re-baseline reviewers confirmed that overall cost impacts due to potential schedule delays are minor. If there is another significant delay in the start of installation, or a prolonged installation period, NSF will trade off installation support against O&M support to remain within the planned annual O&M budget profile.

Management Risk

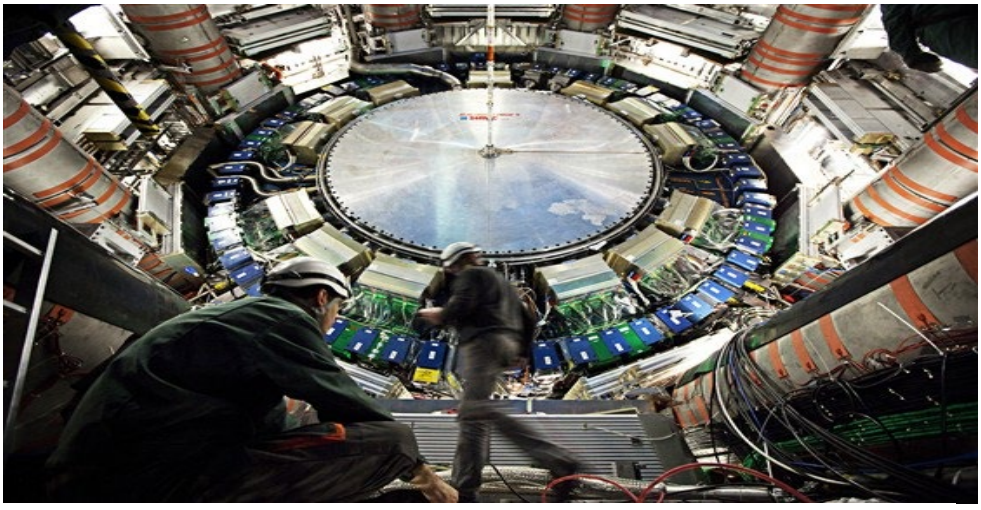
The FDRs established that the management risk was low; the ATLAS and CMS management teams are well-qualified and well-prepared to undertake construction activities, with appropriate organizational

structures and delegations of responsibility. The review committees reported that each team's development of cost and schedule estimates was based on sound (pre-pandemic) 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 could 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 included detailed (pre-COVID) risk management considerations and mitigation strategies. Each project maintains a risk register that is regularly updated (and which includes risks resulting from the pandemic). The management teams are stable. Business Systems Reviews conducted by NSF in late 2022 confirmed that the financial and business management practices used by Columbia and Cornell Universities to administer these awards align with Federal regulations and meet compliance requirements.

Partnership Risk

The NSF scope for the detector upgrades relies on the successful and timely completion of testing by international partners of some key components, such as radiation-tolerant custom electronic circuits that are used throughout both detectors in many HL upgrade applications. That activity is now nearly complete, which enabled a confident evaluation at the spring 2023 re-baselining reviews. Revised schedules and cost estimates and re-evaluation of remaining risks during the re-baselining reviews confirmed that the cost and schedule of the NSF scope is sound.

A further partnership risk arises from possible disruption of the detector fabrication activities that rely, in part, on DOE and NSF research grants to universities. Faculty, post-docs, and graduate students 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 could be confidently addressed. The re-baseline review accounted for COVID-related facility closures and the projects' schedules have been adjusted accordingly. All participating university laboratories and shop facilities in the U.S. are now open.



View of the ATLAS detector. *Credit: CERN.*