HIGH LUMINOSITY UPGRADES TO THE LARGE HADRON COLLIDER (HL-LHC) **$36,000,000**

Appropriated and Requested MREFC Funds for the High Luminosity-Large Hadron Collider Upgrade[1]

(Dollars in Millions)

	FY 2020 Actual	FY 2021 Estimate	FY 2022 Request	FY 2023 Estimate	FY 2024 Estimate	Total Project Cost
Previous Authorized Total Project Cost	$33.00	$33.00	$36.00	$33.00	$18.00	$153.00
Estimate prior to Rebaseline	$33.00	$33.00	$36.00	$33.00	$18.00	$153.00

[1] COVID-19 impacts are not yet fully quantifiable. The situation is evolving rapidly. Schedule and cost impacts will lead to revisions of the current funding plan.

Brief Description

The FY 2022 Request for HL-LHC is $36.0 million. This funding will support ongoing component upgrades of two distinct projects: the "A Toroidal LHC ApparatuS" (ATLAS) and "Compact Muon Solenoid" (CMS) detectors that will operate at the HL-LHC. This is the third year of a five-year construction program that began in FY 2020, near the onset of the COVID-19 pandemic. The FY 2022 Request amount supports the current NSB authorized Total Project Cost (TPC) of $153.0 million. As discussed below, assessment of the COVID-19 impacts is under way using a range of assumptions. It will be refined through a re-baselining of the HL-LHC program once there is a stable and quantifiable understanding of the pandemic's consequences. See the Baseline History section below for more details on the approval timeline and refer to the Project Status section for a summary of the current understanding of COVID-19 impacts.

The 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 is designed to accelerate and collide counter-propagating bunches of protons at a total energy of up to 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.

Scientific Purpose

The LHC probes the fundamental structure of matter to elucidate the basic forces that have shaped our Universe since the beginning of time and that will determine its fate. Studies are carried out by colliding protons and heavy ions at the highest energies ever produced in a laboratory and recording, reconstructing, and analyzing the by-products of these collisions within the ATLAS and CMS detectors.

The discovery of the Higgs boson in 2012 was one of the original goals of the LHC. It is one of the most important discoveries of the last 50 years in particle physics, confirming the existence of the final element of the Standard Model of Particle Physics. Despite the predictive power of the Standard Model, there is strong evidence that it is incomplete. For example, it does not account for the existence of dark matter, nor does it explain why the mass of the Higgs particle is so low. Now, with the High Luminosity Upgrade to the LHC (HL-LHC), the scientific focus has shifted to understanding the detailed properties of the Higgs boson and its coupling to other known processes to elucidate possible deviations from expectations—deviations that might indicate new physical phenomena beyond those described by the Standard Model. In addition, the HL-LHC will continue to search more broadly for new particles and interactions.

Baseline History

Following an agreement between NSF, DOE, and CERN ("Experiments Protocol I"), signed in December 1997, NSF began support for ATLAS and CMS detector construction and software development in 1998. NSF has subsequently supported ongoing O&M, 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 enabling the detectors to function at much higher collision rates in conjunction with an upgrade to the LHC to increase its luminosity. The ATLAS and CMS groups, comprised of researchers from all participating countries, each developed scoping documents describing their scientific goals and the technical paths 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 major facility level to enable meaningful participation by NSF-supported scientists in the HL-LHC research program. An estimated $150.0 million funding envelope was defined by NSF in consultation with the MPS AC.

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.

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 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 targeted the estimated TPC at $150.0 million, or $75.0 million for each detector.

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. The NSF Director obtained the NSB's authorization, in February 2020, to begin construction in FY 2020, with separate construction awards to Columbia and Cornell Universities (for ATLAS and CMS, respectively) totaling $153.0 million (adjusted upward by $3.0 million in the Final Design Review process; see Reviews section below).

Project Status

The ATLAS and CMS Final Design Reviews (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 they offered suggestions to NSF on areas to follow closely during construction. NSF and the NSB conducted additional assessments that assured each project was ready to start construction in April 2020. NSF's Large Facilities Office (LFO) led an independent cost estimate of each project as part of the overall cost analysis process carried out by BFA. These were completed and satisfactorily reconciled prior to awarding construction funds in FY 2020.

Each project is currently (as of mid-FY 2021) about 10 percent complete, but well behind schedule due to the pandemic. Enabling preparatory work by CERN-led international consortia to develop custom silicon

sensors and custom integrated circuits utilized by both detectors is nearly one year behind schedule, which has delayed the start of some NSF-supported construction activities.

Summary of COVID-19 Impacts

The pandemic is causing schedule and cost impacts to the NSF-funded scope for the LHC detector upgrades. Fabrication activities have progressed more slowly than anticipated because of pandemic restrictions on activities in university labs and workshops. Delays in the availability of custom silicon sensors and chips, which are part of each upgrade, are due to the closure during 2020 of radiation test facilities needed to validate their radiation hardness. The full extent of the impacts of the COVID-19 pandemic on this program are not quantifiable as the situation is evolving rapidly. The pandemic is expected to delay the schedules of international partners in each detector upgrade, disrupting linkages to NSF-funded activities. NSF will initiate a process to assess and validate a revised Total Project Cost once the cumulative impacts of the pandemic are understood.

Quantifiable forecasting of schedule delays and cost increases is not yet available, although the ATLAS and CMS management teams are periodically modeling future scenarios to bracket the expected longer-term impacts of the pandemic on the upgrade program. This modeling quantitatively forecasts the pandemic impacts on tasks needed to deliver each of the upgraded detector subsystems based on assumptions as to how the pandemic will evolve and the societal responses that will employed in response. From these assumptions, ATLAS and CMS estimate factors such as labor efficiency, costs to establish and maintain safe working environments, escalation costs arising from schedule delays, and contingency costs arising from re-estimation of future risks due to COVID-19. Estimates are periodically updated as understanding of COVID-19 continues to evolve.

Cost impacts realized since MREFC-funded construction began April 1, 2020 are relatively small (less than 10 percent) in comparison to the pre-pandemic estimate of the total project cost to NSF. This is because initial construction activities are mostly focused on detailed production design work, procurement, and software development—activities that are being accomplished through remote telework. However, work restrictions within university laboratories, workshops, and test facilities and the consequent labor inefficiencies are resulting in schedule delays that grow as the pandemic continues. Effects on industrial suppliers are another source of uncertainty in projecting longer-term impacts. Site visits to vendors are currently not possible, delaying final procurement negotiations. Some vendors may have diminished capacities to meet pre-pandemic delivery forecasts. This has become especially apparent for semiconductor fabricators, where a world-wide surge in demand is straining production capacity. This is expected to affect many industries that need these products, in addition to the LHC detector upgrade activities. CERN's governing body is closely monitoring these and other impacts of the pandemic on HL-LHC plans at the international level. Their deliberations could result in revision to the HL-LHC schedule, although none have been announced so far.

Meeting Intellectual Community Needs

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. 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 is upgrading the accelerator, which will be renamed the High Luminosity-LHC, to deliver the high intensity proton beams required. The HL-LHC will commence ten years of operation in mid-2027. During that time, it is expected to produce more than 10 times the data collected by LHC operation through 2024 (a hundred-fold increase relative to the data set confirming 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. The accelerator enhancements and the detector upgrades are currently planned to be installed and commissioned from 2025 through mid-2027, although CERN may revise these plans in response to the pandemic.

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 25 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, the Office of Budget, Finance, and Award Management (BFA), EHR, OISE, the Office of the Director, the Office of the General Counsel, and the Office of Legislative and Public Affairs. Within BFA, LFO 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 Department of Energy (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 superseded in March 2018 to encompass HL-LHC activities.

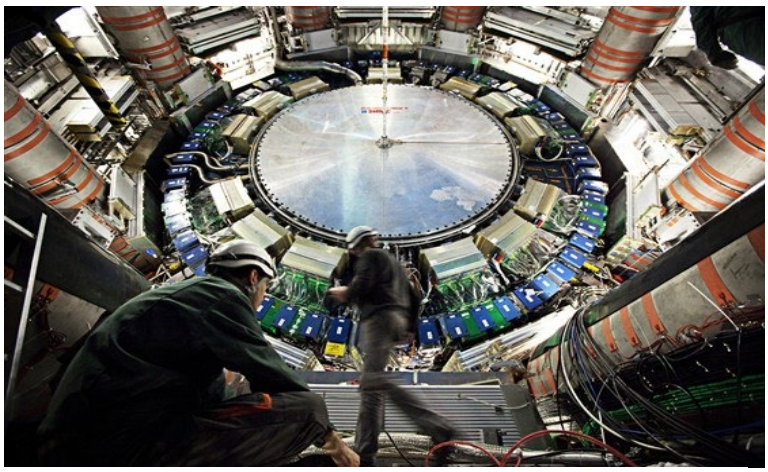
External Governance Structure

NSF-funded principal investigators at Columbia University and Cornell University are responsible for managing the projects and 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 with 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 receives monthly reports from ATLAS and CMS that describe the technical and financial status of NSF-funded construction activities and that update assessments of project risks. The monthly reports also document all revisions to the scope, budget, and schedule baselines, which are implemented through NSF-approved change-control processes. In those cases where revisions exceed thresholds defined in the cooperative agreements for construction, ATLAS and CMS separately submit them to NSF for approval prior to making baseline adjustments.

Partnerships and Other Funding Sources

More than 45 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 about 7,000 participants worldwide. NSF is working closely with DOE to coordinate construction activities and to jointly oversee each detector's operation.



View of the ATLAS detector. *Credit: 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 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 the HL-LHC. Subject to availability of appropriated funds, NSF's total contributions to the HL-LHC Upgrade program are specified and incorporated under separate implementing arrangements in the form of addenda to the 2015 cooperation agreement. The CERN LHC Resources Review Boards (RRBs; 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 oversee and approve all LHC upgrade plans and major decisions at the international level.

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 to CERN to meet the international integration schedule planned for CY 2025-2027. A significant delay could have resulted 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 seven percent of the international detector upgrade program.

The major facility construction project will be completed when the NSF-funded apparatuses for both detectors are delivered and verified at CERN to be in good working order. NSF will fund the subsequent installation, integration, and system testing at CERN through awards to U.S. ATLAS and U.S. CMS collaborations for detector O&M. These activities will be coordinated by CERN. This work is currently planned to occur during CY 2025-2027 (but may be revised by CERN at some future point to account for the impacts of the COVID-19 pandemic). NSF's share of installation and commissioning costs was

estimated before the pandemic outbreak at about $5.0 million per detector. The annual O&M cost is forecast to remain constant during and following the HL-LHC Upgrade installation.

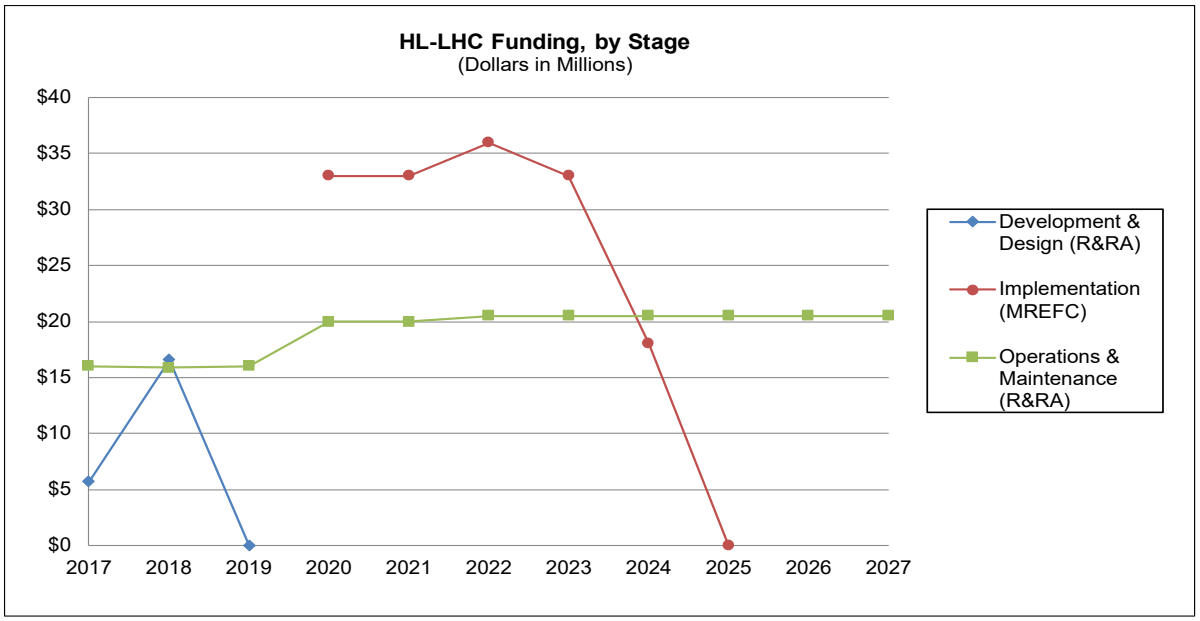
Total Funding Requirements for HL-LHC Upgrade[1]
(Dollars in Millions)

	Cumulative Prior Years	FY 2020 Actual	FY 2021 Estimate	FY 2022 Request	ESTIMATES[2] FY 2023	FY 2024	FY 2025	FY 2026	FY 2027
R&RA:									
Development & Design	$24.31	-	-	-	-	-	-	-	-
Operations & Maintenance[3]		20.00	20.00	20.50	20.50	20.50	20.50	20.50	20.50
Subtotal, R&RA	$24.31	$20.00	$20.00	$20.50	$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**	**$53.00**	**$53.00**	**$56.50**	**$53.50**	**$38.50**	**$20.50**	**$20.50**	**$20.50**

[1] COVID-19 impacts are not yet fully quantifiable and the situation is evolving rapidly. Schedule and cost impacts will lead to revisions of the funding

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

[3] This represents operations support for the current LHC facility. Installation, integration, and system testing of the upgraded detectors was planned to be coordinated by CERN during 2025-2027 (prior to the emergence of COVID-19). NSF's share of installation and commissioning costs was estimated at $5.0 million per detector, which was planned to be funded from the FY 2025-2027 O&M budgets. Evolving understanding of COVID-19 impacts may necessitate altering these plans.



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 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 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 (held before the onset of COVID-19 pandemic) indicated that these operating cost projections are reasonable and are based on realistic assumptions. These projections will be regularly revisited during the period of construction to incorporate evolving understanding of the pandemic impacts 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. NSF conducted external reviews ("Full Life-Cycle Cost Reviews") of the impacts of future computing needs on the operations program during HL-LHC operation. 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 now underway are promising, and only a subset needs to be successful to meet the needs of the HL operating program.

Reviews

- Conceptual Design Reviews (CDR): March 2016 (ATLAS); March and April 2016 (CMS). 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.
- Preliminary Design Reviews (PDR): January 2018 (ATLAS); December 2017 (CMS). 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.
- 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).
- Final Design Reviews (FDR): September 2019 (ATLAS and CMS). 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 under development by CERN and international partners.
- Full Life-cycle Cost Reviews: NSF held reviews of the cost impacts of the MREFC upgrades on the LHC operations program in October 2019.
- Reviews of ATLAS and CMS installation plans and software and computing R&D are planned in July 2021 to confirm the viability of scope, budget, schedule, and risk projections for these activities as part of NSF's assessment of its support for O&M during 2022-2026.
- Reviews of ATLAS and CMS HL upgrade activities are planned in August 2021 to examine the current technical, financial, schedule, and risk status of each project and their current assessments of total pandemic impacts.

Risks

Technical Risk

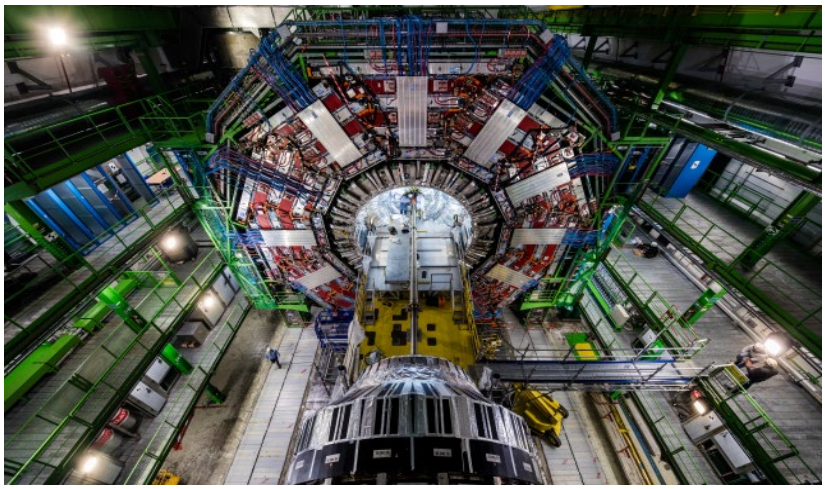
Technical designs were sufficiently mature at the start of construction to credibly support estimates of the costs to complete construction. Cost and schedule impacts due to technical risks are credibly bounded. There are multiple alternatives for dealing with the known production uncertainties, although the unanticipated impacts of the pandemic have introduced uncertainties in supply chain issues and substantially delayed access to radiation testing facilities needed to verify design performance.

Deployment Risk

The MREFC project concludes 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. 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 if there is a longer-than-expected time interval between delivery of the NSF-funded elements to CERN and the start of their installation (which NSF supports through its funding of ATLAS and CMS O&M programs). If pandemic impacts are prolonged, this could result in changes to installation and commissioning requirements and methods. This might lead to greater installation costs or longer durations than originally anticipated. A significant delay in the start of installation, or a prolonged installation period, may increase demands on NSF's O&M support beyond 2027.

Management Risk

The FDRs established that 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 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).



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

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. COVID-19 impacts on international partners, as well as impacts on foreign suppliers of components for the NSF-funded scope, add new schedule and cost risks to those considered when construction budgets were developed.

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. These pre-COVID assessments did not consider the possibility that the pandemic would close some university laboratories and shop facilities and restrict the level of student and post-doctoral fellow participation in hands-on activities associated with testing and characterizing detector components. Ongoing and future risk assessments will take into account COVID impacts.

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-$2 million (not escalated).