HIGH LUMINOSITY-LARGE HADRON COLLIDER UPGRADE (HL-LHC) $38,000,000

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

	FY 2020	FY 2021	FY 2022	FY 2023 Estimate	FY 2024 Request	Total Project
Previous Authorized Total Project Cost	$33.00	$33.00	$36.00	$33.00	$18.00	$153.00
Preliminary Est. of Future COVID-19 Impact[1]	-	-	-	-	20.00	20.00
Estimate prior to Rebaseline	**$33.00**	**$33.00**	**$36.00**	**$33.00**	**$38.00**	**$173.00**

[1] COVID-19 impact estimates are preliminary and not yet fully substantiated. Ongoing schedule and cost impacts will lead to revisions of the current funding plan through a re-baseline process.

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), the 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 the 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 seven percent of the global high luminosity upgrade effort at the LHC, which is being supported by 45 funding agencies internationally.[1]

NSF's FY 2024 Request for HL-LHC is $38.0 million to continue support for ongoing component upgrades of the ATLAS and CMS detectors. The baseline $18.0 million of the FY 2024 Request amount supports the current NSB-authorized Total Project Cost (TPC) of $153.0 million. For planning purposes, a preliminary estimate of an additional $20.0 million is incorporated into the FY 2024 funding profile (which would raise the TPC to $173.0 million) to address the direct and indirect impacts on the project from COVID-19, historically high inflation, supply-chain delays, and the Russian attack on Ukraine (both Russia and Ukraine participate in LHC research and detector upgrade activities).

NSF is working closely with the project management of the ATLAS and CMS detector upgrade

[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.

programs to more fully understand these impacts on the overall costs and schedules to complete planned activities. The current estimates will be refined through a re-baselining of the HL-LHC detector upgrade program that NSF plans to conduct in the spring of 2023, when it is anticipated that there will be a stable and quantifiable understanding of the consequences of these impacts on the NSF-funded scope. The re-baselining is expected to confirm and quantify the need for additional MREFC funding above the current authorized TPC of $153.0 million. If an increase to the TPC is authorized by NSB, NSF plans to obligate additional budget to each of the detector upgrade efforts in late FY 2024 and early FY 2025 to remediate these impacts. 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.

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 the 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 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 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. An estimated $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, NSB authorized the NSF Director to include construction of the High Luminosity upgrades to the ATLAS and CMS detectors in a future Budget Request. Funding to begin construction was provided in the FY 2020 MREFC appropriation, and 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).

Project Status

Each project is currently (as of December 2022) more than one-third complete. Due to the impacts of the COVID-19 pandemic and the other factors mentioned above, both projects are well behind their original schedules.

[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.

Summary of COVID-19 Impacts

The pandemic has resulted in schedule delays and cost increases. Early in the pandemic, universities closed laboratories and workshops where fabrication activities had been planned, although these were later re-opened after instituting health safety restrictions that reduced labor efficiency. COVID-19 also slowed the work undertaken by CERN and foreign partners to develop several custom application-specific integrated circuits (ASICs) planned for use in many subsystems of the ATLAS and CMS detectors, delaying scheduled activities supported by NSF and many other funding agencies. The pandemic also resulted in the temporary closure of radiation test facilities used to evaluate the radiation hardness of custom sensors and integrated circuit prototypes. It impacted industry as well, slowing vendor deliveries of some highly specialized materials and electronic components needed for the detector upgrades.

Relatively small cost impacts have been realized so far (approximately $2 million) because many initial project activities, coinciding with the early stage of the pandemic, involved detailed production design work, procurements, and software development activities that could be accomplished through remote telework. Normal activities have now resumed in the labs and workshops at the U.S. universities involved in the NSF-supported scope. Impacts from supply chain delays and exceptional inflation still pose risks, and these impacts are becoming better understood as vendors provide bids and delivery schedules for production quantities of key components.

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 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. In June 2022, the CERN Council announced its intent to end cooperation with Belarus and Russia (in June and December 2024, respectively) in response to Russia's ongoing aggression against Ukraine.

ATLAS and CMS management teams are revising their detector upgrade project plans to account for impacts of the pandemic and the other factors mentioned above in preparation for NSF's spring 2023 re-baselining review. These revisions will include the additional pandemic-related costs already realized, and they will quantitatively forecast all impacts on remaining tasks that must be accomplished to deliver each of the upgraded detector subsystems. The ATLAS and CMS teams will revise their construction plans to update factors such as labor efficiency, costs to establish and maintain safe working environments, escalation costs arising from schedule delays, revised material and labor costs, assumption of a proportional share of the undelivered Russian/Belarusian scope, and contingency costs arising from re-estimation of future risks due to COVID-19. For planning purposes, NSF has incorporated an estimate of $20.0 million in the FY 2024 Request to account for COVID-related needs. If additional funding is required after the full re-baseline analysis, it will be incorporated into the FY 2025 request.

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 is planned to commence ten years of operation in 2028. During that time, it 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 Director, the Office of the General Counsel, and the Office of Legislative and Public Affairs. Within BFA, the Large Facilities Office (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 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. 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. The Boards 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 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.

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 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 project 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 outbreak 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

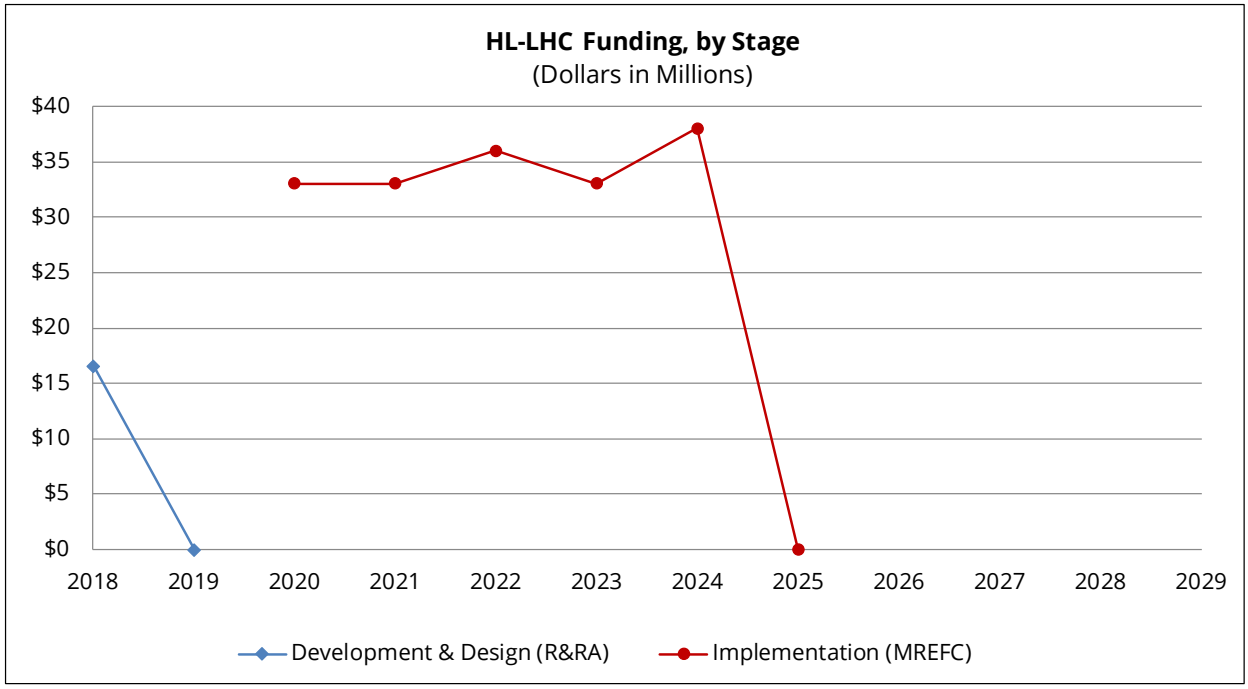
(Dollars in Millions)

	Prior Years	FY 2022 Actual	FY 2023 Estimate	FY 2024 Request	ESTIMATES[1] FY 2025	FY 2026	FY 2027	FY 2028	FY 2029
R&RA:									
Development & Design	$24.31	-	-	-	-	-	-	-	-
Operations & Maintenance[2]		-	-	-	TBD	TBD	TBD	TBD	TBD
Subtotal, R&RA	$24.31	-	-	-	-	-	-	-	-
MREFC:									
Implementation[3]	66.00	36.00	33.00	38.00	-	-	-	-	-
Subtotal, MREFC	$66.00	$36.00	$33.00	$38.00	-	-	-	-	-
TOTAL REQUIREMENTS	**$90.31**	**$36.00**	**$33.00**	**$38.00**	**-**	**-**	**-**	**-**	**-**

[1] Outyear estimates are for planning purposes only. The current cooperative agreements end in December 2026 (CMS) and January 2027 (ATLAS) - see LHC request in the Major Facilities section.

[2] FY 2025 and beyond are TBD because COVID-19-related delays are increasingly likely to move the operations phase of HL-LHC past this reporting window.

[3] COVID-19 impacts are preliminary. An estimate of an additional $20.0 million in COVID-related funding need is incorporated in the FY 2024 Request for planning purposes. Schedule and cost impacts will lead to revisions of the funding plan.



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 software research programs now underway to address these challenges 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.

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, 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 Operation. 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.

- Rebaselining reviews of the CMS and ATLAS detector upgrades will be held in March and April 2023, respectively. The external reviews and NSF's Internal Cost Assessment of the budget and schedule changes requested will be used to confirm MREFC funding needed in FY 2024 and any potential funding needs 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 total project cost of the NSF-funded construction projects is not anticipated to increase due to the expanded time interval between delivery of the NSF-funded elements to CERN and CERN's recently revised start of installation (which NSF supports through its funding of ATLAS and CMS O&M programs). If pandemic impacts are prolonged, this could result in additional changes to installation and commissioning requirements and methods, but external reviews 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 flat overall annual O&M budget profile planned.

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.

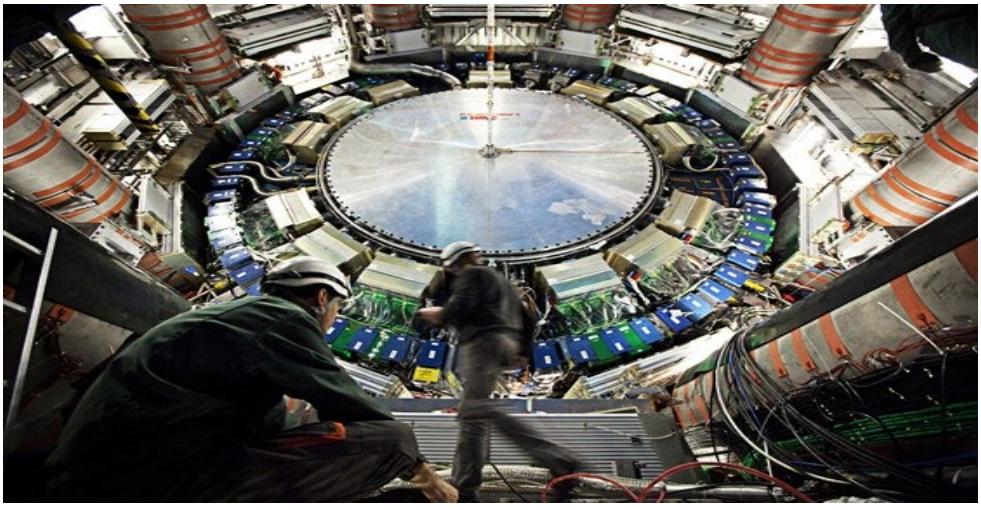
Partnership Risk

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 will enable a confident evaluation at the Spring 2023 rebaselining reviews. COVID-19 impacts on international partners, as well as impacts on foreign suppliers of components for the NSF-funded scope, added new schedule and cost risks to those considered when construction budgets were developed. Revised schedules and cost estimates and re-evaluation of remaining risks will be assessed during the Spring 2023 rebaselining reviews.

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. As most of the fabrication of production quantities of various detector components occurs later in the construction schedule, only minor impacts from this risk have been realized so far, and all participating university laboratories and shop facilities in the U.S. are now open.

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).



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