

LARGE HADRON COLLIDER (LHC) – ATLAS AND CMS

\$20,500,000
+\$500,000 / 2.5%

Large Hadron Collider Funding (Dollars in Millions)

| FY 2021 Actual | FY 2022 (TBD) | FY 2023 Request | Change over | |
|-------------------|------------------|--------------------|----------------------------|---------|
| | | | FY 2021 Estimate Amount | Percent |
| \$20.00 | - | \$20.50 | \$0.50 | 2.5% |

Brief Description

LHC, an international project at the European Organization for Nuclear Research (CERN) laboratory in Geneva, Switzerland, is the world's most powerful particle accelerator. It produces the highest energy particle beams ever created in a laboratory, making it the premier facility in the world for research in elementary particle physics. LHC is a superconducting accelerator ring approximately 16.5 miles in circumference, in which counter-circulating proton beams can collide with a total energy of up to 14 TeV (one TeV= 10^{12} electron volts). The collisions occur at four discrete interaction points around the circumference of the accelerator where highly sophisticated detectors measure the characteristics of the debris produced in the proton-proton collisions. LHC can also collide beams of heavy ions, such as lead.

Scientific Purpose

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. Among the possible unknowns are extra dimensions of space, unification of fundamental forces, and evidence for dark matter candidates in the Universe. Studies are carried out by colliding protons and heavy ions at extremely high energies and recording, reconstructing, and analyzing the by-products of these collisions using two large detectors: A Toroidal LHC Apparatus (ATLAS) and the Compact Muon Solenoid (CMS).

The discovery of the Higgs boson in 2012 was one of the original goals of LHC and is one of the most important particle physics discoveries of the last 50 years. Now the scientific focus has shifted to understanding the detailed properties of the Higgs boson and other known processes to elucidate possible deviations from expectations — deviations that might indicate new phenomena. In addition, LHC continues to search for new particles and interactions, including supersymmetry, dark matter, and other unknown phenomena.

This scientific focus has motivated the High Luminosity (HL) upgrades to LHC and its detectors, which will allow for the collection of a much larger data sample. NSF is supporting upgrades to ATLAS and CMS as part of a large global effort (See the HL-LHC narrative for more information).

Status of the Facility

LHC is the only experimental particle physics facility operating at the high energy frontier. The facility and the planned HL-LHC upgrades are a high priority of the entire high energy physics community. The LHC energy upgrade in 2015 from 8 TeV to 13 TeV pushed the boundaries of our understanding

into unknown territory. CERN is carrying out a multi-year program to increase the beam interaction rate that will culminate with HL-LHC operation beginning in 2027. This will produce a large data sample of rare events that could shed light on new physics. Installation of smaller-scale detector upgrades, completed in 2021, will enable ATLAS and CMS to keep pace with LHC's performance enhancements through 2025. A shutdown that CERN is currently scheduling to begin in 2025 (which may be delayed because of pandemic considerations) will enable the installation of major upgrades to the accelerator and detectors preparatory to ten years of HL-LHC operation, extending the scientific reach of the facility.

COVID-19 impacts on the operations of LHC have been relatively minor so far. Activities at CERN to prepare the ATLAS and CMS detectors for the next cycle of accelerator operations, starting in April 2022, were completed on schedule. U.S. scientists and international colleagues conducted hands-on detector support activities that followed carefully orchestrated protocols to ensure worker safety. Additionally, most NSF-supported activities associated with ATLAS and CMS detector operation are concentrated in the software and computing areas, which are well suited for remote work in a safe environment.

Meeting Intellectual Community Needs

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 (plus about 30 of the nearly 1,300 members of LHCb collaboration, which operates the separate LHCb experiment at LHC). Research at LHC is supported by NSF through the Division of Physics Elementary Particle Physics and Nuclear Physics programs.

In addition, a world-wide cyber infrastructure effort, the Worldwide LHC Computing Grid (WLCG), is dedicated to LHC data processing, allowing scientists to remotely access and analyze vast data sets. The U.S. ATLAS and CMS collaborations continue to lead the development and exploitation of distributed computing within their respective international collaborative efforts. The WLCG Tier 1 and Tier 2 computing centers (funded by DOE and NSF, respectively) enable the researchers at 98 U.S. universities and five national laboratories to access LHC data and computing resources and thus train students in both state-of-the-art science and computational techniques.

Governance Structure and Partnerships

NSF Governance Structure

NSF oversight is provided by a program officer in the MPS Division of Physics (PHY), who works cooperatively with staff from other MPS divisions, BFA, the Office of the General Counsel, and the Office of Legislative and Public Affairs. Within BFA, the Large Facilities Office provides advice to program staff and assists with agency oversight and assurance. The MPS facilities team and the Chief Officer for Research Facilities also provide high-level guidance, support, and oversight.

External Governance Structure

NSF/PHY staff and their Department of Energy (DOE) Office of Science counterparts meet twice yearly with CERN and funding agencies from other nations at Resource Review Board (RRB) meetings, where

Major Facilities

technical and financial issues are discussed and decided. The ATLAS and CMS experiments are each funded by more than forty different agencies, including NSF and DOE. NSF and DOE coordinate U.S. investments in the LHC program through a Joint Oversight Group (JOG), which also meets at least semi-annually.

The U.S. ATLAS and U.S. CMS collaborations internally select leadership that represent the United States within the international ATLAS and CMS collaborations. The international leadership for each collaboration establishes its respective scientific goals and objectives and exercises overall governance. NSF supports detector operation through two awards—one to the University of Nebraska-Lincoln for CMS, and another to Stony Brook University for ATLAS. The current awards, which were implemented following thorough external review and comprehensive internal assessment during FY 2021, expire in December 2026 and January 2027, respectively.

Partnerships and Other Funding Sources

U.S. activities at CERN are enabled by a DOE/NSF/CERN agreement signed in 1997 (“Experiments Protocol I”) and a Cooperation Agreement, signed in May 2015 and renewed every five years. An additional agreement signed in December 2015 (“Experiments Protocol II”) further defined the framework for NSF participation in the particle physics programs of the ATLAS and CMS detector collaborations under the auspices of CERN. These activities include expanding the physics reach of the detectors through construction of technologically advanced enhancements able to take full advantage of the increase of the LHC accelerator’s nominal luminosity by a factor of ten. The resulting increase in capabilities will facilitate and support the continued participation of the large U.S. particle physics community engaged at LHC during the HL-LHC era. The HL-LHC is slated to operate for ten years beginning in 2027.

Funding

Annual operations and maintenance funding covers the costs of NSF-provided detector components, software and computing, and contributions to a common fund to maintain shared detector infrastructure. Detector operation and maintenance are forecast to require future levels of effort like those needed to support the current apparatus. Data handling is an exception, in which extraordinary efforts by CERN, the experimental collaborations, and funding agencies are now underway on a global scale to support HL-LHC operation beyond 2027.

Total Obligations for LHC

(Dollars in Millions)

| | FY 2021 | FY 2022 | FY 2023 | ESTIMATES ¹ | | | | |
|--------------------------|---------|---------|---------|------------------------|---------|---------|---------|---------|
| | Actual | (TBD) | Request | FY 2024 | FY 2025 | FY 2026 | FY 2027 | FY 2028 |
| Operations & Maintenance | \$20.00 | - | \$20.50 | \$20.50 | \$20.50 | \$20.50 | \$20.50 | \$20.50 |

¹ Outyear estimates are for planning purposes only. The current cooperative agreements ended in December 2026 (CMS) and January 2027 (ATLAS).

The FY 2023 Request for the NSF LHC program is \$20.50 million. Funds will support operation activities by U.S. university-based researchers participating in high energy physics at LHC. LHC is planned to restart in April 2022 and to resume full-time operation in July 2022. This follows the successful conclusion of the three-year data-taking period in December 2018, and the completion of detector maintenance and the installation of detector performance enhancements that began in 2019.

Reviews

NSF and DOE conduct separate and joint external reviews of operations and detector upgrade activities. Each agency is fully cognizant of the activities of the other partner, and recommendations from reviews are routinely used to inform ATLAS and CMS operations planning and the agencies' oversight thereof. Two JOG review meetings per year assess operational performance, scientific and financial status, management issues, and plans for future activities. DOE and NSF conducted joint external panel reviews of ATLAS and CMS operations at the end of January 2022. The most recent JOG was held in October 2021 and the next one is planned for March 2022.

Renewal/Recompetition/Termination

NSF awarded operations funding to CMS and ATLAS through five-year cooperative agreements beginning in FY 2022. The ATLAS award was a renewal of the prior five-year award. The CMS award was to a new awardee. The awards were implemented after NSF completed a proposal-driven review process that included external review and cost analysis of each detector's operations proposal. NSF has no ownership of any part of the facility. CERN has taken responsibility for disposal of all irradiated apparatus at the conclusion of experimental activity. No divestment is planned at this stage.