LARGE HADRON COLLIDER (LHC) – ATLAS AND CMS **$20,000,000**
+$4,000,000 / 25.0%

Large Hadron Collider Funding
(Dollars in Millions)

FY 2019 Actual	FY 2020 (TBD)	FY 2021 Request	Change over FY 2019 Actual Amount	Percent
$16.00	-	$20.00	$4.00	25.0%

The Large Hardon Collider, an international project at the European Organization for Nuclear Research (CERN) laboratory in Geneva, Switzerland, is the most powerful particle accelerator ever constructed. It produces the highest energy particle beams ever created at a laboratory, making it the premier facility in the world for research in elementary particle physics. The LHC is a superconducting particle accelerator, approximately 16.5 miles in circumference, where 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. The LHC can also collide beams of heavy ions, such as lead. Major "high luminosity" upgrades to the accelerator and detectors are planned to be installed during a suspension in operation that is planned for 2025-mid-2027. The upgrades will significantly enhance the performance of the accelerator and the detectors so that they will be able to gather more than ten times the total amount of data collected previously. Detailed information on the upgrades can be found in the High Luminosity LHC (HL-LHC) narrative in the MREFC chapter.

More than 45 international funding agencies provide support for scientists to participate in experiments at the LHC. Participating scientists have self-organized into distinct scientific collaborations to operate each of the detectors at the LHC. U.S. participation in the LHC scientific program is defined by Memoranda of Understanding and supporting agreements among NSF, the Department of Energy (DOE), and CERN. CERN is responsible for carrying out the overall LHC program goals of operation and maintenance, planning and leading the implementation of upgrades to the accelerator, detectors, and research infrastructure, and achieving scientific goals. As the host laboratory, CERN is responsible for coordinating international participation in the LHC program. The United States, through a partnership between the DOE and NSF, made major contributions to the construction and operation of the A Toroidal LHC ApparatuS (ATLAS) and Compact Muon Solenoid (CMS) detectors, two large general-purpose particle detectors at the LHC. NSF additionally supports operation of the LHCb experiment, a special purpose detector that focuses on studying the properties of elementary particles containing b (or "bottom") and anti-b quarks. Researchers funded by NSF and DOE comprise the U.S.-ATLAS and U.S.-CMS collaborations, while the U.S.-LHCb collaboration is supported only by NSF. Currently, about 1,270 U.S. researchers participate in the ATLAS and CMS collaborations, including more than 100 post-doctoral fellows and about 450 students, of whom more than 250 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 contingent (plus about 30 of the 1,282 members of the LHCb collaboration).

LHC data have resulted in major scientific discoveries. Foremost of these was the July 2012 announcement by the ATLAS and CMS collaborations of the discovery of a particle having properties consistent with the long-sought Higgs boson, a prediction of the Standard Model of particle physics. Its existence was a prediction of the theoretical framework describing the origin of the masses of elementary particles. The experimental confirmation of this theory at the LHC led to the award of the 2013 Nobel Prize in physics to François Englert and Peter Higgs. In 2018, the ATLAS and CMS collaborations announced observations of Higgs bosons coupling to pairs of t (or top) and b (bottom) quarks. Observing these extremely rare

processes is a significant milestone for the field of high-energy physics as it allows physicists to test critical parameters of the Higgs mechanism in the Standard Model. The new results may also provide insight into one of the most puzzling aspects of the Standard Model: the wide range of masses among fermions, the class of particles that constitute matter and includes quarks and leptons. This analysis relied on the abundant data produced to confirm, with overwhelming statistical significance, that the strengths of these couplings are consistent with the predictions of the Standard Model.

The ATLAS and CMS collaborations continue to search for evidence of new physical phenomena beyond the Standard Model. The overall LHC research program includes searches for particles predicted by various proposed extensions to the Standard Model. These searches utilize the Higgs boson as a tool for discovery: investigating how it interacts with itself, searching for its possible coupling to dark matter, and scrutinizing the data for anomalies indicative of unanticipated phenomena. The experimental results to date have helped tighten constraints on different models and possibilities, homing in on the most exciting areas of investigation ahead. Further accumulation of data enables these investigations to be carried out with ever-greater precision as researchers look for small, but statistically significant, deviations of measurements from theoretical predictions.

This FY 2021 Request for the NSF LHC program funds operation activities by U.S. university-based researchers participating in high energy physics at the LHC. In FY 2017-FY 2019, LHC operations funding was reduced while planning for the high luminosity upgrade was underway. As of FY 2020, HL-LHC planning will have been completed and construction will begin. The LHC will resume full-time operation in May 2021, following a shutdown in 2018 and maintenance and installation of performance enhancements in 2019. The LHC's successor, the HL-LHC, and its concomitant detector upgrades, will be installed during a shutdown planned to run from the beginning of 2025 through mid-2027.)

Total Obligations for LHC
(Dollars in Millions)

	FY 2019	FY 2020	FY 2021	ESTIMATES[1]				
	Actual	(TBD)	Request	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026
Operations & Maintenance	$16.00	-	$20.00	$20.50	$20.50	$20.50	$20.50	$20.50

[1] Outyear estimates are for planning purposes only. The current cooperative agreemenst ends December FY 2021 (CMS) and January 2022 (ATLAS).

A global cyber-infrastructure, the World-wide LHC Computing Grid or WLCG, is dedicated to LHC data processing, allowing scientists to remotely access and analyze vast data sets. The U.S.-ATLAS and U.S.-CMS collaborations continue to lead the development and exploitation of distributed computing within their respective international collaborative efforts. The WLCG and the Tier 2 computing centers funded by NSF enable the researchers at 92 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.

The High Energy Physics Advisory Panel, through the May 2014 report of its Particle Physics Project Prioritization Panel, recommended to DOE and NSF that the highest priority strategic goal for the U.S. particle physics research program, within a global context, should be continued support for involvement in the LHC program. Within the scope of supported activities, they recommended including design and development planning for the high luminosity upgrades. These upgrades will increase the luminosity, or proton-proton interaction rate, tenfold compared to the LHC's initial operating capabilities. This will necessitate significant enhancements to the detectors to exploit this scientific opportunity. NSF has been working with the U.S.-ATLAS and U.S.-CMS collaborations to plan for a possible contribution to this upgrade. Supplemental funds provided through the LHC operations award in FY 2016-FY 2018 enabled the U.S.-ATLAS and U.S.-CMS collaborations to prepare and complete their construction-ready planning. Subject to final NSB authorization, NSF plans to begin funding elements of the high luminosity detector

upgrades to ATLAS and CMS in FY 2020.

Through the participation of young investigators, undergraduate and graduate students, and minority-serving institutions, the U.S.-LHC program serves the goal of helping to produce a diverse, globally-oriented workforce of scientists and engineers. Innovative education and outreach activities allow high school teachers and students to participate in this project.

Management and Oversight

- NSF Structure: A program director in the MPS Division of Physics is responsible for day-to-day project oversight. The Division of Acquisition and Cooperative Support in BFA provides financial and administrative support. An Integrated Project Team, with representatives from MPS, experienced program officers from other directorates within NSF, the Large Facilities Office (LFO) and other divisions in BFA, contributes to planning and oversight activities. The MPS Facilities team, together with the NSF Chief Officer for Research Facilities, also provide high-level guidance, support, and oversight.
- External Structure: U.S. program management occurs through a Joint Oversight Group (JOG), created by NSF and DOE. The JOG has the responsibility to see that the U.S.-LHC program is effectively managed and executed to meet commitments made under the LHC international agreement and its protocols. NSF operations support is provided through cooperative agreements with Princeton University for U.S.-CMS and with Stony Brook University for U.S.-ATLAS.
- Reviews: NSF and DOE conduct separate and joint external reviews of operation and detector upgrade activities. Each agency is fully cognizant of the activities of the other partner. Two joint review meetings per year assess operational performance, scientific and financial status, management issues, and plans for future activities. DOE and NSF conducted joint reviews of ATLAS and CMS operations in May 2019. The most recent JOG was held in October 2019. The next major joint review of operations will be held in June 2020. NSF conducted Final Design Reviews of the ATLAS and CMS upgrades in September 2019. In October 2019, NSF conducted external reviews of the budget impacts of the MREFC upgrades on the ATLAS and CMS operations programs.

Renewal/Recompetition/Termination

Funding for operations and maintenance for the NSF LHC program was renewed in FY 2017 following external review of proposals from ATLAS and CMS. NSF's review process culminated in the implementation of cooperative agreements for operation that will expire in FY 2022. ATLAS and CMS periodically conduct internal competitions among the U.S. universities within each collaboration to select the NSF PI and host institution for the Cooperative Agreement for operation. This process preceded the current awards, and it will be repeated prior to submission of the LHC operations proposal in FY 2022.