PARTICLE PHYSICS

Large Hadron Collider Seeks New Particles after Major Upgrade

Long-awaited boosts to the world's most powerful collider could spur breakthroughs in the hunt for physics beyond the Standard Model

By Daniel Garisto on April 27, 2022

Large Hadron Collider tunnel. Credit: Maximilien Brice/CERN

In their final moments, the last protons flew at nearly the speed of light. They completed the 27-kilometer loop underneath the Alpine countryside 11,245 times a second until they were released from their metal coil and slammed into a giant steel-coated graphite block. Since December 2018, other than a few tests here and there, the Large Hadron Collider (LHC) has been offline. But on April 22 the LHC fired up again and commenced its third run.

“The accelerator has been off for three years,” says Freya Blekman, an experimental particle physicist at the Compact Muon Solenoid (CMS) detector at the LHC. “So there’s people who have never been in the control room..., never have done shifts where data was taken. And for them, it’s extremely exciting.”

Located on the border between France and Switzerland, the LHC is the crown jewel ofCERN, the European Organization for Nuclear Research near Geneva. By nearly every measure—funding, personnel, physical size—the LHC is the largest particle physics experiment in the world. In 2012 two LHC experiments, A Toroidal LHC ApparatuS (ATLAS) and CMS, discovered the Higgs boson and completed a five-decade search for the origins of elementary particle mass. Although researchers tout other results, such as the discovery of pentaquarks, these scientific results have sometimes been overshadowed by the sense that the LHC has failed for not discovering "new physics" beyond the Standard Model, the successful but incomplete account of elementary particles and forces that govern them.

Over the past few years, far from sitting idle, the powered down LHC has been a buzz of activity. Engineers have started to upgrade the collider's capabilities to improve its "luminosity," essentially a measure of how many particle collisions there are likely to be in a square centimeter per second. Meanwhile physicists have boosted their detectors to keep pace with an increased number of collisions resulting from the higher luminosity. Researchers have also developed new analyses to better sift through haystacks of data to find proverbial needles.

As Run 3 begins, particle physicists face a number of tantalizing anomalies, from the new, unexpectedly hefty measurements of the W boson mass to the long-standing muon g−2 discrepancy, but they lack firm evidence of new physics. "There aren't any obvious flashing lights," says Nishita Desai, a theorist at the Tata Institute of Fundamental Research in India. "It's not like 'this is where you will get a discovery.'"

While other avenues to discovering new physics exist, colliders remain vital. There is no better way to learn about fundamental particles than to smash them together and examine the wreckage. With prospects for another collider to supersede it still decades away, the LHC is perhaps particle physicists' best hope to discover what lies beyond the Standard Model.

SOMETHING OLD, SOMETHING NEW

By the turn of the millennium, particle physicists were putting the finishing touches on a theory of the universe's building blocks. Collider data showed that protons and neutrons are made of quarks strongly bound together by aptly named gluons. Fission and fusion occur when quarks exchange W bosons. The lightest pair of quarks, up and down, are followed by the heavier charm and strange quarks and then the even weightier bottom and top. Similarly, electrons have heavier cousins, muons and taus, which are identical to electrons but for their mass. Broadly, these particles were divided into fermions, which make up matter, and bosons, which carry forces.

This grand theory, perhaps unimaginatively dubbed the "Standard Model," left plenty of folks unsatisfied. For one, it was silent on gravity. The Standard Model also said nothing about dark matter or dark energy—two mysterious phenomena that account for more than 95 percent of mass in the universe. In particular, physicists itched to know where the particles of the Standard Model got their mass.

Theorists in the 1960s posited that particle mass arose from an imperceptible field permeating all of space: the more a particle interacts with this field, the greater its mass. Peter Higgs, a British theorist, suggested that the field would have an associated particle—the Higgs boson. Discovering it would confirm the mechanism that gave elementary particles their mass.

After a bumpy few first years, ATLAS and CMS announced on July 4, 2012, that they had discovered a "Higgs-like" particle of about 125 times the mass of a proton.

It was a historic accomplishment, the culmination of decades of work—not just from physicists but engineers, electricians, computer technicians, custodial staff, and more. Finding the Higgs was not a shock, however. "I think people would have been more shocked if you didn't find anything," Desai says.

Between 2013 and 2015, LHC took its first long shutdown to repair and make small upgrades. Then, from 2015 to 2018, the LHC conducted its second run and smashed more particles at almost double its previous run's energy. Hopes were still relatively high for new physics. When ATLAS and CMS reported hints of a new particle around 750 giga-electron-volts (GeV) in 2015, theorists leaped at the chance and published hundreds of papers on the anomaly. Many papers suggested it was a hint of supersymmetry (SUSY), a class of theories in which bosons have fermion counterparts, and vice versa—a new symmetry between matter and forces. Photons would be mirrored by photinos; quarks would be mirrored by squarks. These supersymmetric counterparts were thought to be hiding out of sight, at higher masses. Naming conventions aside, SUSY theories were attractive to physicists because the existence of supersymmetric particles could simultaneously explain the Higgs's low mass and provide a candidate for dark matter. But as more information came in, the bump in the data turned out to be a statistical anomaly, not a new particle.

"There's a certain generation of physicists who were told that, as soon as the accelerator turned on, they would see SUSY [and] find new physics." Blekman says. "But there is no reason why it should be so easy."

Discovery-hungry scientists have begun searching in other directions, such as long-lived particles (LLPs). When physicists look for new heavy particles, they assume a fleeting lifetime—the hefty 125 GeV Higgs boson lives for less than a billionth of a trillionth of a second. An LLP, however, could linger long enough to move out of the detector's typical field of vision before decaying. During the third run, LHC detectors will use improved analyses to catch LLPs they might have missed before.

The success of the Standard Model and failure to "break" it has led to accusations that particle physicists are facing a crisis, that they have been wandering in a desert for 40 years. For Desai, this narrative has it all backward. "In fact, I would say that particle physics is perhaps emerging from a crisis, which we did not realize we were in before, because everybody was working on the same thing," she says. "There are no easy answers, and I think most younger people are quite happy about that."

BUILT TOO VAST

Upgrading the largest machine in the world would be nothing short of a monumental effort, even if its critical infrastructure was not 100 meters underground.

After each multiyear run, the LHC's equipment requires refurbishing.. José Miguel Jiménez, CERN's head of technology, who oversaw the second long shutdown, ticks off a rapid-fire list of areas that needed work: "technical infrastructure, cooling, ventilation, electrical distribution, electrical safety, elevators, cranes, all these fancy door access systems [and] fire detection."

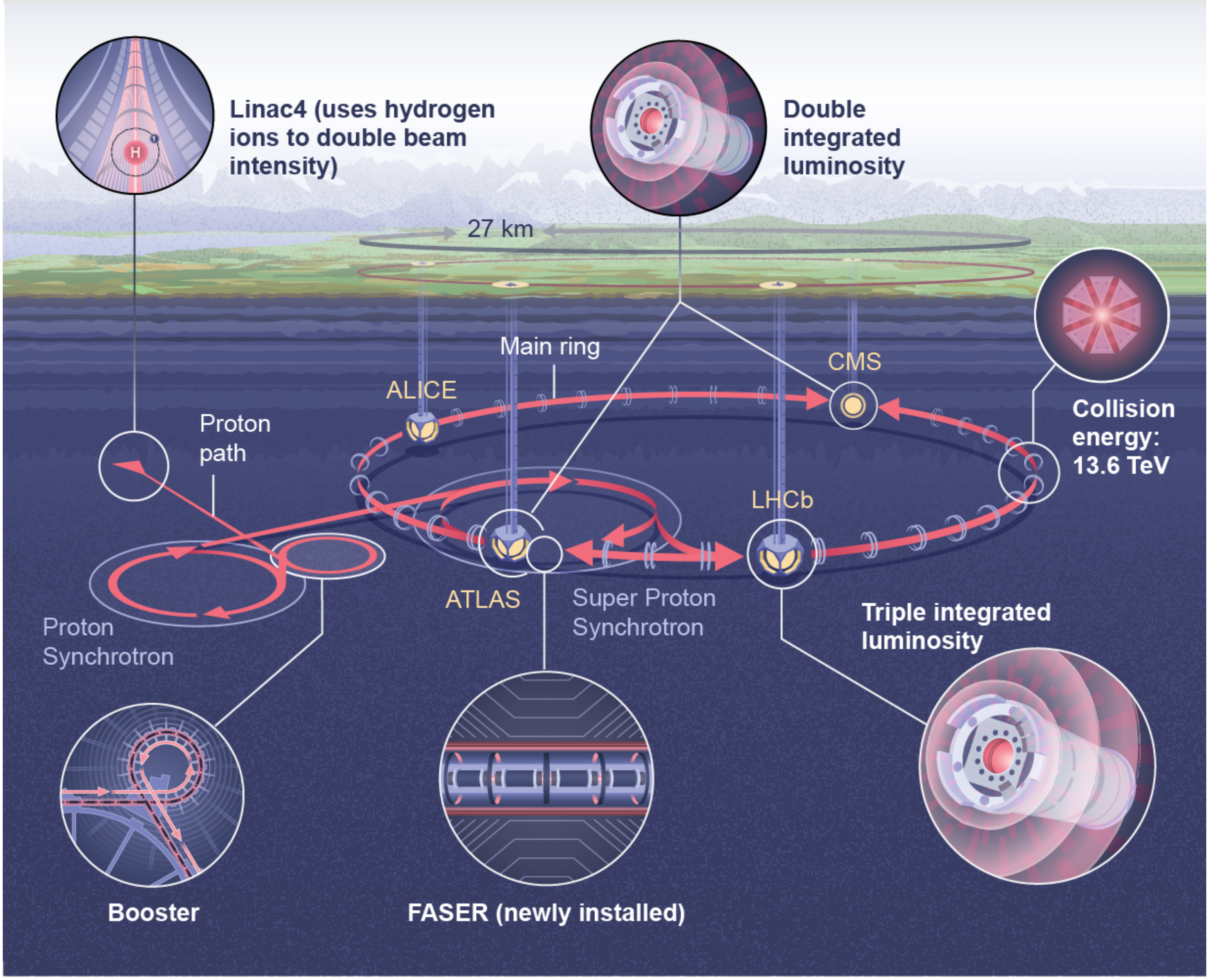
Making repairs is difficult during routine operation because the LHC's critical components must be kept ultracold. About 130 metric tons of liquid helium—about the weight of a midsize blue whale—keep 36,000 metric tons of the collider under 4 kelvin. These components, which include magnets and bubble-shaped accelerating cavities, are chilled so that they can channel the immense electrical currents required for the entire facility's function without any resistance. It takes months to warm up the machine and months more to cool it back down, so even a small problem with cold portions of the machine can take a prohibitively long time to fix.

While the machine was warm, engineers completely replaced the source for the LHC's beams, Linac2—which had been in use since the 1970s—with Linac4; the name Linac 3 was already used for a different accelerator. During Run 3, every particle that collides in the LHC will begin at Linac4 as an electrically charged soup of hydrogen ions—essentially protons with two electrons. Ions from this soup are sent out in "bunches" and accelerated to 160 mega-electron-volts (MeV), more than three times the energy of Linac2.

“By raising the injection energy, you can actually store higher intensities,” explains Jorg Wenninger, head of LHC beam operation. Protons want to repel one another because they share the same charge. But at higher energies, protons generate a magnetic field that counters this repulsion, and more can fit into the same space. Using hydrogen ions and then removing the extra electrons further increases the beam density so that each bunch consists of roughly 120 billion protons squeezed into a diameter of about three microns.

The Large Hadron Collider, Illuminated

An improved “booster” and a new proton beam source called Linac4 have given the upgraded Large Hadron Collider (LHC) at CERN denser, more luminous beams that will yield many more collisions over time. Enhancements to the resolution of the ATLAS, CMS and LHCb experiments at the LHC will help these detectors better handle the resulting flood of collision data. Improved magnets will allow proton collisions to occur at higher energies: 13.6 trillion electron volts (TeV) instead of 13 TeV. And a small new detector called FASER will seek out extremely low-mass particles leaking from ATLAS.



Credit: Nick Bockelman

This density is crucial because it determines how many collisions the detectors at the LHC will eventually see, says Bettina Mikulec, a senior physicist at CERN, who led the injector upgrade. If the beam is not dense at the start, it will not be dense later.

From the injector, the beam enters the booster ring, which now accelerates the protons to 2 GeV, a 43 percent improvement from Linac2. There, the bunches are brought more closely together using a technique called slip stacking. Like cars entering a freeway, proton bunches are merged until the space between them is a mere 25 nanoseconds.

Upon entering the main collider ring, protons encounter new aluminum beam pipes near the detectors. "The problem with stainless steel is that the cobalt inside the metal is getting radioactive by default," Jiménez says, "which is always quite problematic."

To avoid any interference, the beam requires a vacuum as devoid of air as possible. With pressures as low as one ten-trillionth of an atmosphere, the LHC's beamline has been called the emptiest place in the solar system. A proton can travel for hundreds of hours with essentially zero chance of hitting a molecule of air, according to Jiménez.

When it is running, the LHC—not just the magnets and beam but also computers and cryogenics and vacuum systems—consumes an astonishing amount of energy: about 800 gigawatt-hours per year, or about half that of the entire city of Geneva. "We are, in a certain way, the electrical utility for CERN," says Mario Parodi, head of electrical project management. CERN's electricity comes primarily from France, where about 80 percent of the grid relies on nuclear energy. Much of the power to smash nucleons, therefore, comes from splitting nuclei.

As COVID swept across the world, it shut down the shutdown—but only for a bit. CERN locked down on March 24, 2020, but some work resumed as early as May, according to Jiménez. Throughout the rest of the pandemic, teams had to be conscious of issues such as packing people into workspaces. Elevators act like bottlenecks, which made getting underground even more difficult and raised safety issues that were not exclusive to COVID—any kind of tunnel incident could leave workers stranded.

Thanks to careful planning by Jiménez and his team, the start of Run 3 was only delayed by a year.

EVERYTHING IS ILLUMINATED

Though they were not taking data, physicists at detector experiments were busy making repairs and upgrades of their own.

ATLAS is a gigantic tube-shaped machine that is 46 meters long, 25 meters high and about 7,000 metric tons—the weight of the Eiffel Tower's frame. Its counterpart, CMS, is a tightly bound detector half the size of ATLAS but twice its weight. CMS uses a solenoid, a ring-shaped magnet, to bend the path of charged particles such as muons.

Upgrades to the injector to create a denser beam mean that, for Run 3, both ATLAS and CMS will effectively double their luminosity over time. Denser beams mean more collisions, which mean more data, which mean a better chance of finding rare events that could be evidence for new physics.

Dealing with increased luminosity requires taking faster and better data, Blekman says. Both ATLAS and CMS have revamped their "triggers"—systems that use software and hardware to recognize particle events, such as a Higgs boson decaying to two photons. Sifting legible events from a mishmash early on is crucial for later analysis.

Some dismantling was required for these upgrades. CMS, despite its weight, is built from slices that rest on hovercraft-like air pads and can be pulled apart. But moving CMS apart and putting it back together can create micron-size displacements that affect the detector. To ensure things are where they should be, Blekman and her colleagues use the straight lines of cosmic rays passing through the device like a level.

A critical upgrade for ATLAS is the “new small wheels”—the wheels, it should be said, are 10 meters across, not exactly “small,” and do not actually rotate. These thin chambers full of wires will capture the tracks of particles such as muons as they rocket outward from the collision point to the rest of the detector.

Upgrades could lead to the discovery of new particles, but ATLAS and CMS also have other responsibilities. “You have to remember that these experiments are more than just discovery machines. They are also measurement machines,” Blekman says. A better understanding of the particles we know is important science in its own right, and precisely pinning down the parameters of the Standard Model may help future experiments break it.

Whereas ATLAS and CMS underwent moderate upgrades, the Large Hadron Collider beauty (LHCb) detector, which is use particles called beauty quarks, or b quarks, to search for rare decays will be completely changed. “We are going to start commissioning a completely new detector,” says Patrick Koppenburg, an experimental particle physicist at LHCb. “We need a better resolution just so that we can tell [particles] apart.”

LHCb will go from seeing one collision per proton bunch crossing to about six. If a detector’s resolution is too low, it can turn “black”—every pixel is hit by a particle, rendering it useless. Koppenburg and his colleagues have installed much higher-resolution particle trackers that they hope will give LHCb the data to validate enticing anomalies it saw in Run 2.

The newest additions to the LHC are far smaller than their cohort—one new detector could fit snugly in a suitcase. The Forward Search Experiment (FASER) is designed to detect new featherweight particles, such as those connected to the dark sector, and FASERnu is designed to detect well-known particles: neutrinos.

Both detectors are situated in a snug tunnel separated from ATLAS by a few hundred meters of solid earth. Only feebly interacting particles such as neutrinos or as yet unknown dark sector particles can make the journey. Luckily, any lightweight particles from ATLAS collisions are highly focused. “Roughly speaking, about 90 percent of [the particles] actually pass through a piece of paper held 480 meters away,” says Jonathan Feng, a physicist at the University of California, Irvine, and co-founder of FASER. “If we made it bigger, we wouldn’t actually increase the event rate too much.”

FASER is essentially a mostly empty tube full of trackers designed to detect a dark sector particle decaying. FASERnu uses the opposite strategy. “We want as dense of a material as possible to get the neutrinos to actually interact,” Feng says. The detector is essentially made from camera film interleaved with 1,000 tungsten plates. Tungsten’s high density—nearly twice that of lead—gives neutrinos more targets to scatter off. At the end of data taking, the tungsten-film sandwich is retrieved and analyzed. What it sacrifices in temporal resolution—it has none—it makes up for in spatial resolution, which will allow Feng and his colleagues to even identify the millimeter-long track from a tau neutrino decay.

For the newest experiments on the block, there is essentially no room for disappointment. “We have basically guaranteed interesting physics,” Feng says about FASERnu. “And then we have speculative, revolutionary physics.” If FASER actually sees a dark sector particle, even a small detector could usher in big new physics.

WATCHING, WAITING

As Run 3 starts, physicists have already pushed the beam to its new maximum energy of 6.8 tera-electron-volts (TeV), exceeding the previous energy record set by the LHC and making it the highest energy particle beam humans have ever created. "So far it is going very well," Wenninger says. Still, it will take time to straighten out any kinks. The first collisions, which will be at much lower energies, are expected to begin in about a month.

“We don’t know what is working, what is not immediately working,” Koppenburg says. To calibrate detectors like LHCb, the researchers will have to “[rediscover] the Standard Model particles one by one.” Only once they have ascertained that photons look like photons, electrons look like electrons, and so on, can they have confidence in their results.

Even if everything works as planned, discoveries take time. A detector might spot hints of a new particle at the start of Run 3, but it could take years for scientists to comb through the massive trove of data and sort out all of the uncertainties before making any conclusions.

In the meantime, theorists will continue to puzzle over anomalies and dream up hypothetical particles that could be responsible for the discrepancies detectors have seen. Engineers are not disinterested parties, either. “We are watching very carefully what the experiments are doing,” Jiménez says. “We can create the technology for future projects and future physics, but we can’t discover anything. I mean, the discovery comes from the detector.”

As for the detectors, the injectors, the magnets, the thousands of tonnes of ultracold collider? All of those come from the hard work done during the shutdown.

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Daniel Garisto is a freelance science journalist covering advances in physics and other natural sciences. His writing has appeared in *Nature News, Science News, Undark*, and elsewhere.

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