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Large Hadron Collider resumes collecting data at new record energy

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Physicists operating the Large Hadron Collider (LHC) are once again circulating beams of high-energy protons along the 27-kilometer-long circular particle accelerator. The LHC was shut down in 2018 for scheduled maintenance and numerous upgrades, all of which have borne fruit over the past four years, the most notable being the new record collision energy of the accelerator of 13.6 TeV (teraelectronvolts, a unit of mass/energy in particle physics).

The upgrades include improvements to the hardware which detects and records collisions, as well as new computers to process the vast quantity of data derived from these expected to be collected in the coming years. The two main detectors, ATLAS and CMS, are expected to record more data than the previous two runs combined. Of two additional detectors, work on the LHCb is predicted to increase its ability to gather data by a factor of 10 and ALICE will likely record more than 50 times the number of collisions than in previous runs.

Two brand new detectors were also installed for the current run, FASER and SND@LHC, both of which are designed to explore the physics of neutrinos.

The LHC is an international physics collaboration located at CERN (the European Organisation for Nuclear Research) and straddles the border between Switzerland and France. It is operated and used by tens of thousands of researchers from hundreds of universities and institutions from more than 100 countries across all six inhabited continents. It has operated since 2009 and stands as a monumental achievement as both a scientific and social endeavor.

The collider operates by injecting protons, hydrogen atoms each stripped of its electron, into two counter-rotating beams and then accelerating them to just under the speed of light. The beams are then focused by a series of powerful superconducting magnets into four points around the ring and forced to ram into each other, producing conditions that mimic the high energy conditions theorized to have existed in the first moments of the Universe. Each of the four main experiments—ATLAS, ALICE, LHCb and CMS—are located at one of the four focusing points and are used by particle physicists to study in different ways the physical properties of the particles that are produced by these extraordinarily energetic collisions.

The most famous result produced by the LHC is the confirmation of the existence of the Higgs boson during the first run of the collider from 2009 to 2013. During that time, collisions were carried out at then-record energies of 7 TeV and 20 petabytes (20 million gigabytes) of data were recorded. Hints of the Higgs boson emerged in 2011 and CERN announced a discovery of a new fundamental particle in 2012. To confirm the results, the LHC delayed its initial scheduled shutdown into early 2013 to allow enough data to be collected to confirm the Higgs discovery. The second run of the collider gathered 10 times as much data, and the current one starting will multiply this by yet another factor of at least 10.

The search for the Higgs ultimately comes from the search for the “atom” (that which cannot be cut smaller), first postulated by the ancient Greek philosopher/scientist Democritus. The atoms of the periodic table were given that name when the Russian chemist Dimitri Mendeleev first formulated the periodic table of the elements in 1869. Mendeleev classified each pure chemical into “families” with similar properties. In doing so he simultaneously gave order to the chemicals that were known and predicted the existence and properties of many that were yet to be discovered. Several of the as-yet-undiscovered element germanium's physical properties, for example, were well predicted in advance of its 1886 discovery, to the astonishment of chemists.

Atoms are, however, not the smallest particles of matter. That atoms can transmute themselves was discovered by Henri Becquerel in 1896 as the phenomenon of radioactivity, and that much lighter constituents could be separated from them was proven by J.J. Thomson in 1897 when he used a cathode ray tube to produce a beam of particles with negative charge, what we now call electrons. Several experiments followed in the ensuing decades probing the internal structure of the atom, which led to the discovery of the proton and the neutron, a more complete understanding of radioactive decay and a whole host of discoveries about matter at its smallest scales.

The search for the Higgs boson, however, was a sticking point in the search for a complete model of subatomic particles for decades and was in many ways the impetus for the development of the LHC. It was first theorized in 1964 by Peter Higgs, François Englert and Robert Brout to describe why some particles, like the photon, have no mass, but others, like the W and Z bosons, are quite massive. At the time, the existing physical models predicted that those particles should also have zero mass and were contradicted quite sharply by well-studied experimental data.

Brout, Englert and Higgs developed a mechanism (the BEH mechanism) to explain this discrepancy. The photon and the W and Z bosons were all supposed to have zero mass as a result of a "symmetry" in particle physics between the electromagnetic force, governed by the photon, and the weak force, which describes radioactivity and is governed by the two types of W bosons and the Z boson. The three proposed a "symmetry breaking" mechanism to explain the discrepancies in masses.

Symmetry breaking can be likened to looking into a mirror and raising one's right hand. Imagine that instead of seeing the mirror image of the right hand being raised, you see the mirror image of the left hand being raised. This represents the symmetry being broken, and is possible in the realm of particle physics. The concept has been successfully used to explain a variety of other strange processes that occur in particle physics.

Further research also revealed that the BEH mechanism could explain the masses of the other particles described and at the time predicted by the Standard Model, the "periodic table" of particle physics. The Higgs boson was realized to be critical to understanding the mechanism and the underlying theory as a whole.

The discovery of the Higgs, however, was not the end of the investigation of mass, but a major milestone. One of the main tasks of the second run of the LHC, which went from 2015 to 2018, was to more fully characterize the Higgs boson, the many ways the particle decays and to check that its properties do not change at higher energies. Those measurements, particularly the rate of decay by the Higgs into a pair of subatomic particles called bottom quarks, provided several key measurements that demonstrated in multiple ways how the particle is connected to the mass of other fundamental constituents of matter.

There have been several other major discoveries over the past decade. LHCb, for example, recently announced three brand new particles, one composed of five quarks and two composed of four quarks (protons and neutrons are each composed of three). Quarks are elementary particles that come in six "flavors"—up, down, charm, strange, top, bottom—and are the building blocks for numerous types of matter. They are also key in understanding how matter binds together to form many of particles produced by particle accelerators.

More such studies are expected in the coming months and years. There will be more papers published on the nature of the Higgs boson at even higher energies, as well as other properties of the Standard Model. There are also plans to look for physics beyond the Standard Model, both through observed properties of particles that don't agree with the current theory and by signatures of wholly new particles. The contradictions with what is known and unknown will slowly emerge, leading to the development of models that integrate old and new physics into an even greater whole.

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