MODULE VIII. 1960-2012

THE STANDARD MODEL OF PARTICLE PHYSICS

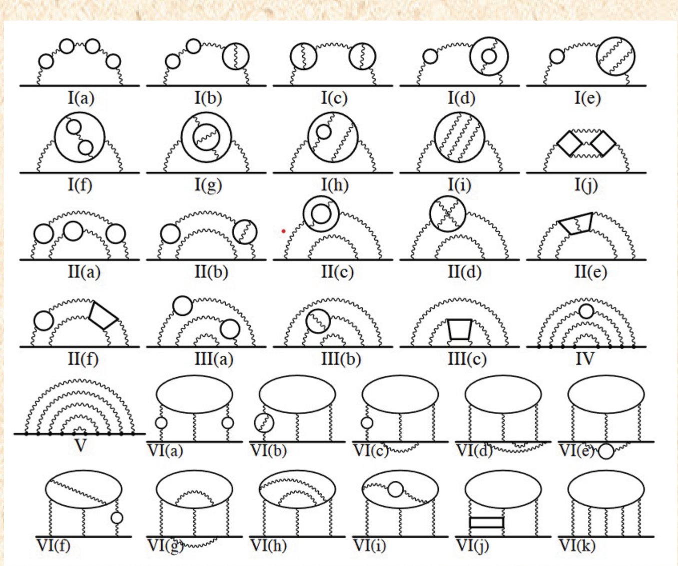
In parallel with the discovery of the large number of particles – the particle zoo – in the 50s, physicists had developed theories that the interactions of the fundamental particles are mediated by exchange particles – gauge bosons – acting as force carriers. One example was the pion. In his 1934 article, Hideki Yukawa argued that the strong nuclear force is carried by a particle with a mass approximately 200 times that of an electron. Yukawa received the 1949 Nobel Prize in Physics for predicting the existence of the pion. Another such example is the photon that is the mediating particle of electricity and magnetism.

STEVEN WEINBERG (1933-2021)

was an American theoretical physicist and Nobel laureate in physics for his contributions with Abdus Salam and Sheldon Glashow to the unification of the weak force and electromagnetic interaction between elementary particles. *(photo: AIP Emilio Segre Visual Archives)*

RISE OF FIELD THEORY

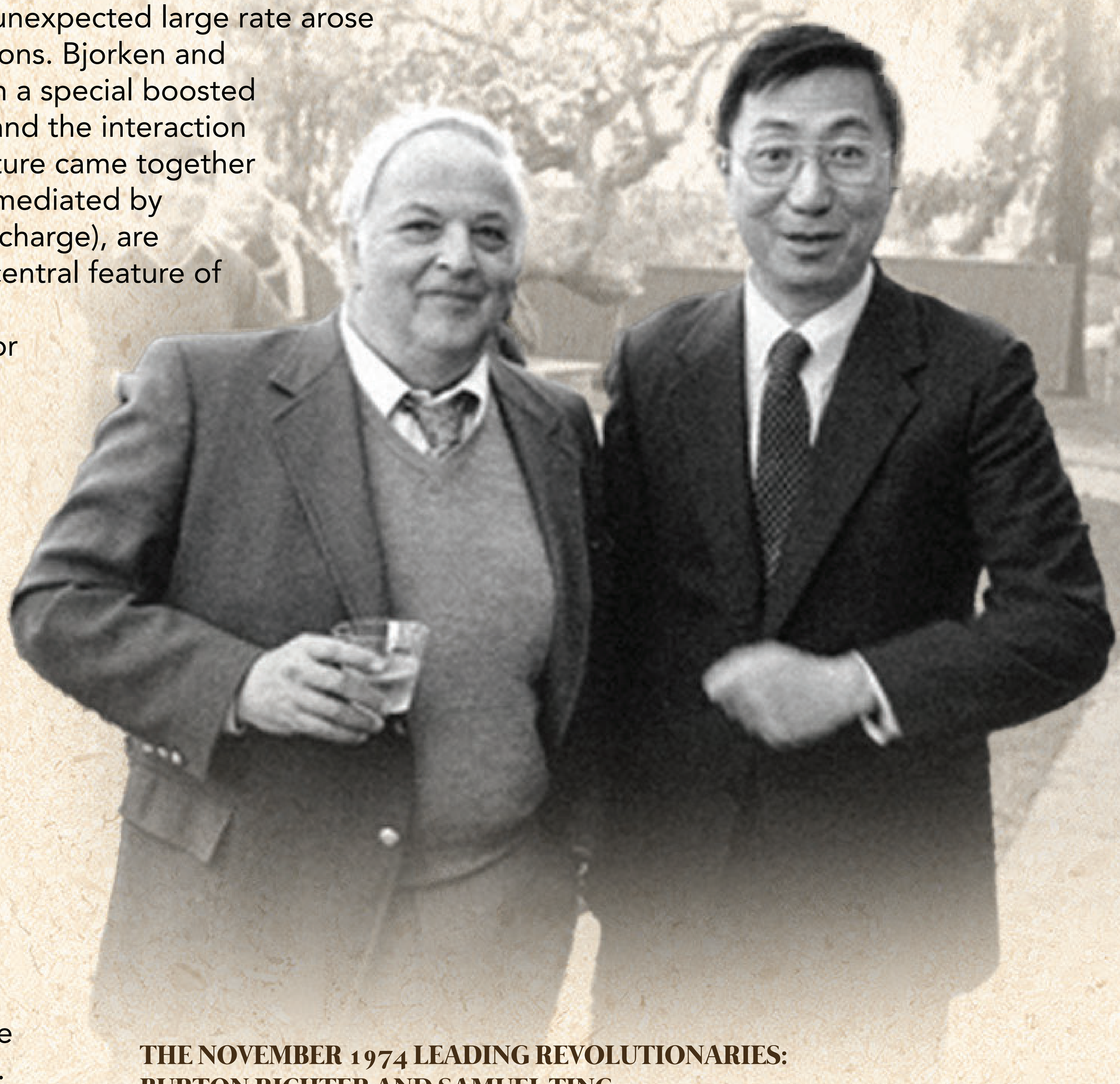
At the beginning of the 1960s, more of such mediating particles had been proposed, along with field theories in which the objects of study are not particles and forces, but quantum fields and their symmetries. One huge problem was that some such theories seemed to suggest massless particles that did not correspond to anything observed. One way of overcoming this problem is via the phenomenon of confinement realized in QCD, where the strong interactions get rid of the massless "gluon" states at long distances. Even if this was portrayed to be a well-understood mechanism to solve this problem, it introduces a mass gap that remains not understood to date – it simply transposed the problem of observing massive particles to the problem of understanding confinement. By the very early 1960s, people had begun to understand another source of massless particles: spontaneous breaking of a continuous symmetry. This led to further acceptance of a theory with both massless and massive particles and led to the unification of two of the four known fundamental interactions of nature: electromagnetism and the weak interaction, in a theory known as the electroweak interaction or the electroweak force. Glashow, Salam and Weinberg were awarded the 1979 Nobel Prize in Physics for their contributions to this unification, known as the Weinberg–Salam theory.



The power of field theories. Vertex diagrams con-tributing to the anomalous magnetic moment of a lepton up to 10th order of calculations in a quan-tum field theory. The solid lines represent lepton lines propagating in a weak magnetic field. Devi-ations from these precision calculations can point to neglected contributions introduced by unknown particles - new physics.

QUARKS ARE FOR REAL!

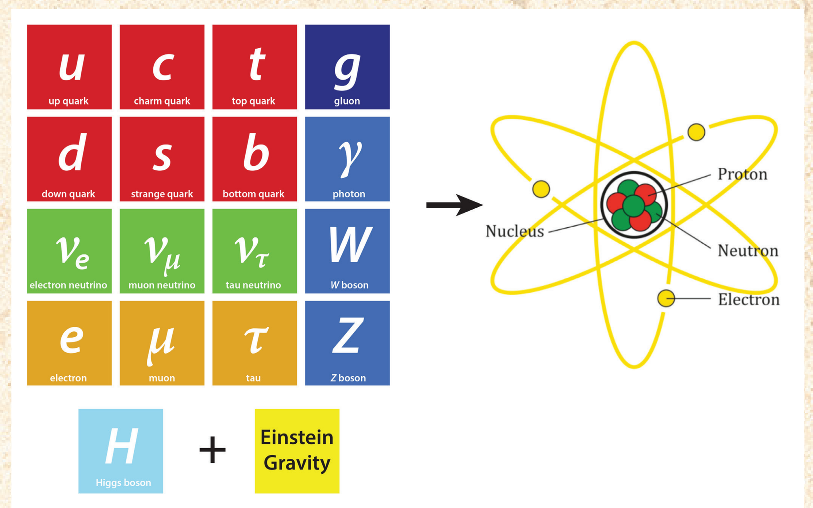
Of particular relevance to our story is the MIT-SLAC experiment that took place in the late 1960s at the Stanford Linear Accelerator Center (SLAC). In 1967, the newly built, 2-mile-long electron accelerator at SLAC enabled a new kind of electron-scattering experiment, known as deep inelastic scattering (DIS), in which the energy is large enough to violently smash the proton target. A group of physicists, led by Henry Kendall and Jerome Friedman of MIT and Richard Taylor of SLAC, measured the scattered electron rate in kinematics where the incident electron lost most of its energy. They observed that the rate in this deep inelastic regime varied slowly with momentum transfer. Analogous to Ernest Rutherford's analysis in Manchester, James Bjorken and Richard Feynman deduced that this unexpected large rate arose from scattering from pointlike, fractionally charged constituents of the proton, so-called partons. Bjorken and Feynman's parton model allowed determination of the quark momentum distributions only in a special boosted reference frame. In this frame, due to relativistic effects, the proton was Lorentz-contracted and the interaction time of the virtual photon with the proton's charged constituents was dilated. The whole picture came together when partons were identified as fractionally charged quarks. The interactions of the quarks, mediated by gluons, each of which carries "color" (literally a type of internal charge analogous to electric charge), are described by the theory of quantum chromodynamics (QCD), developed in the 1970s. One central feature of QCD is "confinement," which is the locking together of quarks in hadrons. Unlike the electromagnetic force, the color force increases in strength as the distance between quarks or quarks and gluons increases, thus explaining why quarks and gluons do not exist as free particles, and why studying them inside nucleons and nuclei with electrons has been and will continue to be valuable to advancing scientific understanding. Nobel Prizes were awarded to Friedman, Kendall and Taylor in 1990 for the SLAC experiments, and to David Gross, David Politzer, and Frank Wilczek in 2004 for their insights into how the color force works.



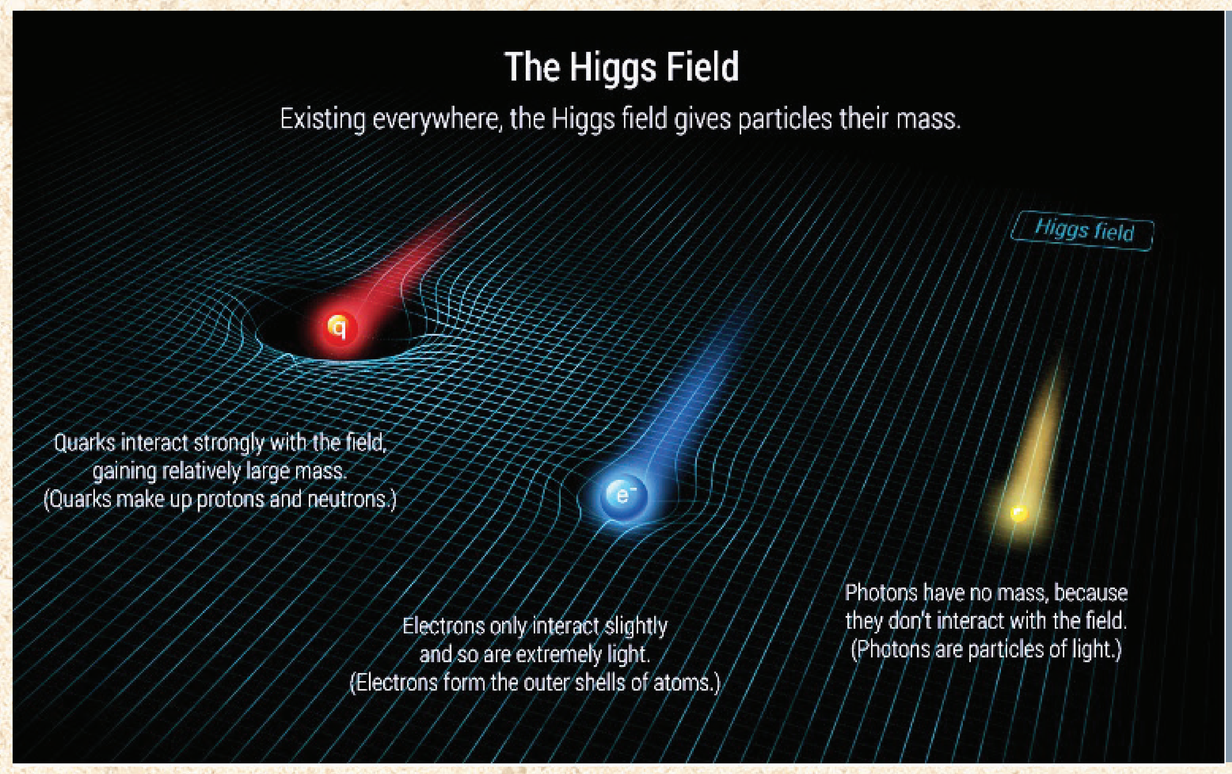
THE NOVEMBER 1974 LEADING REVOLUTIONARIES: BURTON RICHTER AND SAMUEL TING.

THE NOVEMBER 1974 REVOLUTION

The discovery of the J/ψ meson was made independently by two research groups, one at the Stanford Linear Accelerator Center, headed by Burton Richter, and one at Brookhaven National Laboratory, headed by Samuel Ting of MIT. They discovered that they had found the same particle, and both announced their discoveries on November 11, 1974. The importance of this discovery is highlighted by the fact that the subsequent, rapid changes in high-energy physics at the time have become collectively known as the "November Revolution." It was an important milestone in establishing the Standard Model. Richter and Ting were jointly awarded the 1976 Nobel Prize in Physics. The discovery of the J/ψ was highly important for a number of reasons. Firstly, it was a stunning example that demonstrated the quark substructure of matter. Further, the charm quark is relatively heavy and moves comparatively slowly inside the J/ψ meson, so we have a kind of hydrogen atom of the strong interaction. Finally, the charm quark's existence fulfilled the need for it in the unified theory of electromagnetism and weak interactions. Not only was it found, it had the right mass. In the decades following 1974, the Standard Model was completed with the experimental discoveries of the bottom quark at SLAC (1977), gluon at DESY (1979) and top quark at Fermilab (1995). In parallel, the three flavors of neutrino, electron, muon and tau, were established and in 1998 it was discovered that these flavors could oscillate, which implied that they had non-zero mass. What remained elusive until 2012 was the mechanism by which the quarks and leptons obtained mass.



Basic elements of the Standard Model. Shown are the quarks and leptons, which as far as we know have no internal structure and are pointlike, to-gether with the field quanta of the electromagnetic, strong and weak forces. The recently discovered Higgs boson H explains the masses of the particles. Gravitation has not yet been incorporated into the Standard Model.

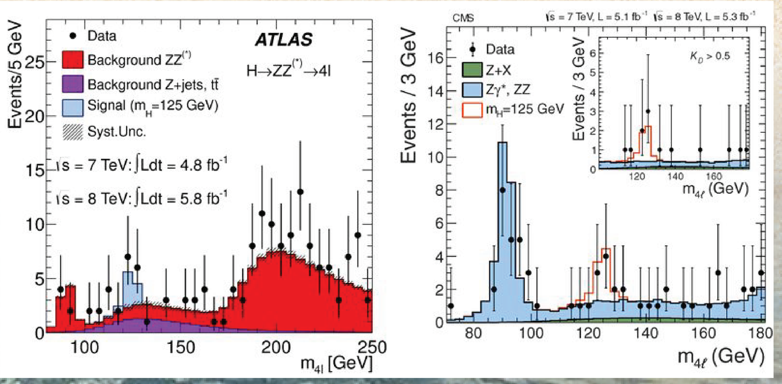


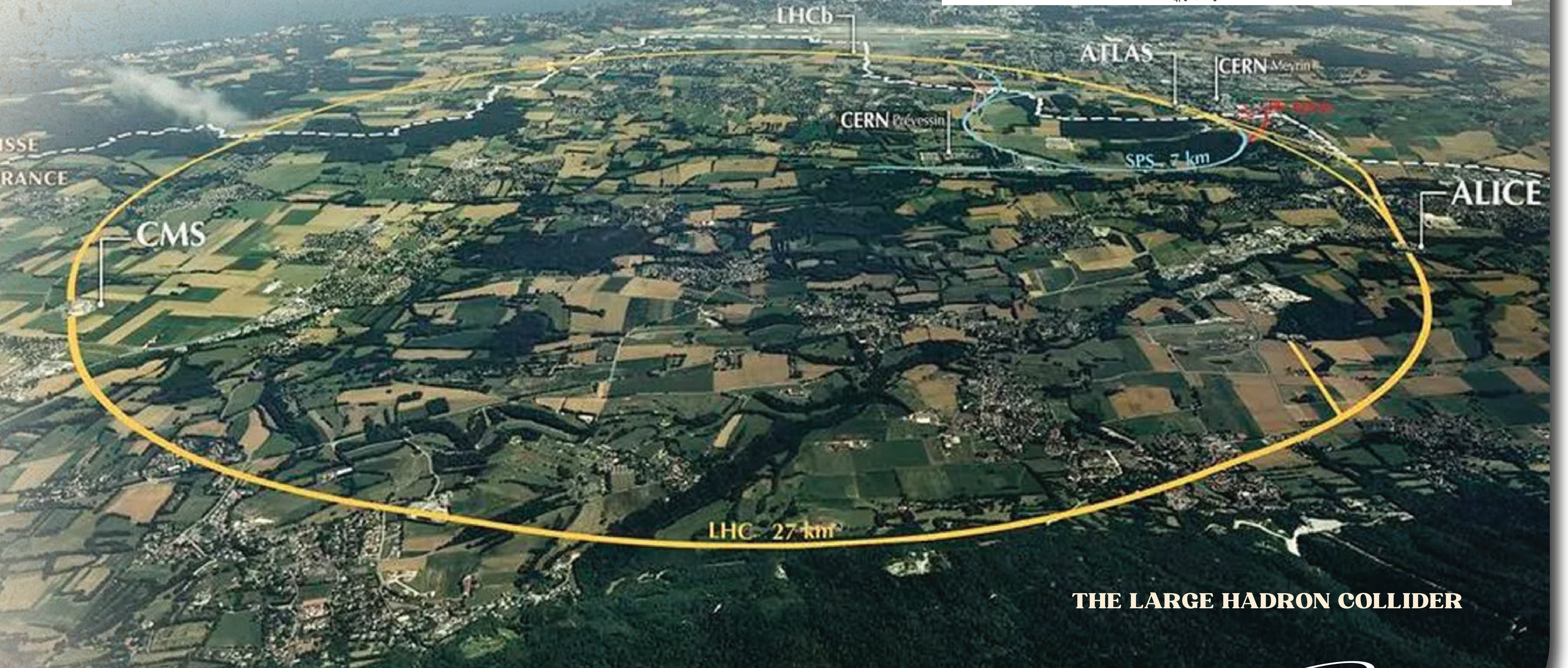
DISCOVERY OF THE HIGGS BOSON IN 2012

The Higgs field is a scalar field that breaks the weak isospin symme-try of the electroweak interaction and, via the Higgs mechanism, gives mass to many particles. Both the field and the boson are named after physicist Peter Higgs, who in 1964, along with others, proposed the Higgs mechanism as a way for some particles to acquire mass. All fundamental particles known at the time should be massless at very high energies, but fully explaining how some particles gain mass at lower energies had been extremely difficult. If these ideas were correct, a particle known as a scalar boson should also exist (with certain properties). This particle was called the Higgs boson and could be used to test whether the Higgs field was the correct explanation. After a 40-year search, a subatomic particle with the expected properties was discovered in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider at CERN near Geneva, Switzerland. The new particle was subsequently confirmed to match the expected properties of a Higgs boson. It had a mass of about 125 GeV – see data on right. Peter Higgs and Fran¸cois Englert were awarded the 2013 Nobel Prize in Physics for their theoretical predictions.

THE STANDARD MODEL OF PARTICLE PHYSICS

The Standard Model is the theory describing three of the four known fundamental forces (the electromagnetic, weak and strong interactions, while omitting gravity) in the universe, as well as classifying the known elementary particle zoo. It was developed in stages throughout the latter half of the 20th century, with the current formulation being finalized in the mid-1970s upon experimental confirmation of the existence of quarks. Of the 117 Nobel Prizes in Physics awarded to date, more than 40 have been awarded for work leading to the development of the Standard Model. Spin is a fundamental aspect of the quantum world. All elementary particles with half-integer spin are known as fermions, and particles with integer spin are known as bosons. The Standard Model includes three families of spin-1/2 fermions, quarks and leptons, categorized by their different masses and characteristics. Leptons live on their own, and quarks live combined in bound systems to form the particle zoo. The Standard Model is summarized schematically on the left. The pointlike fermions (quarks and leptons) interact via exchange of the force-carrier bosons (photon, W±, Z0 and gluons). Together with Einstein's theory of gravity, the Standard Model can explain all measurements in the laboratory. The discovery of the charm quark (1974), confirmation of the top quark (1995) and the tau neutrino (2000) have completed the three families and added further credence to the Standard Model. In addition, the Standard Model has predicted properties of the W and Z bosons with great accuracy. The Standard Model has been enormously successful in providing experimental predictions and is believed to be theoretically self-consistent. The development of the Standard Model also changed the perception of the structure at matter at small distance scales as becoming much more dynamic and less static. The quantum field description invokes the particles and fields to become intertwined, and the near-massless constituents to move at relativistic speeds, using their energies to create and annihilate further particle pairs. Nonetheless, the Standard Model falls short of being a complete theory on all forces as it leaves out gravitation as described by general relativity. It also cannot explain several important phenomena, e.g., the known excess of matter over antimatter in our universe, the known existence of dark matter, and the nonzero neutrino masses. And a huge gap remains between the mass parameters of the Standard Model and the experimental masses of protons, neutrons and nuclei.





THE LARGE HADRON COLLIDER

Created by: Rolf Ent and Richard Milner

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