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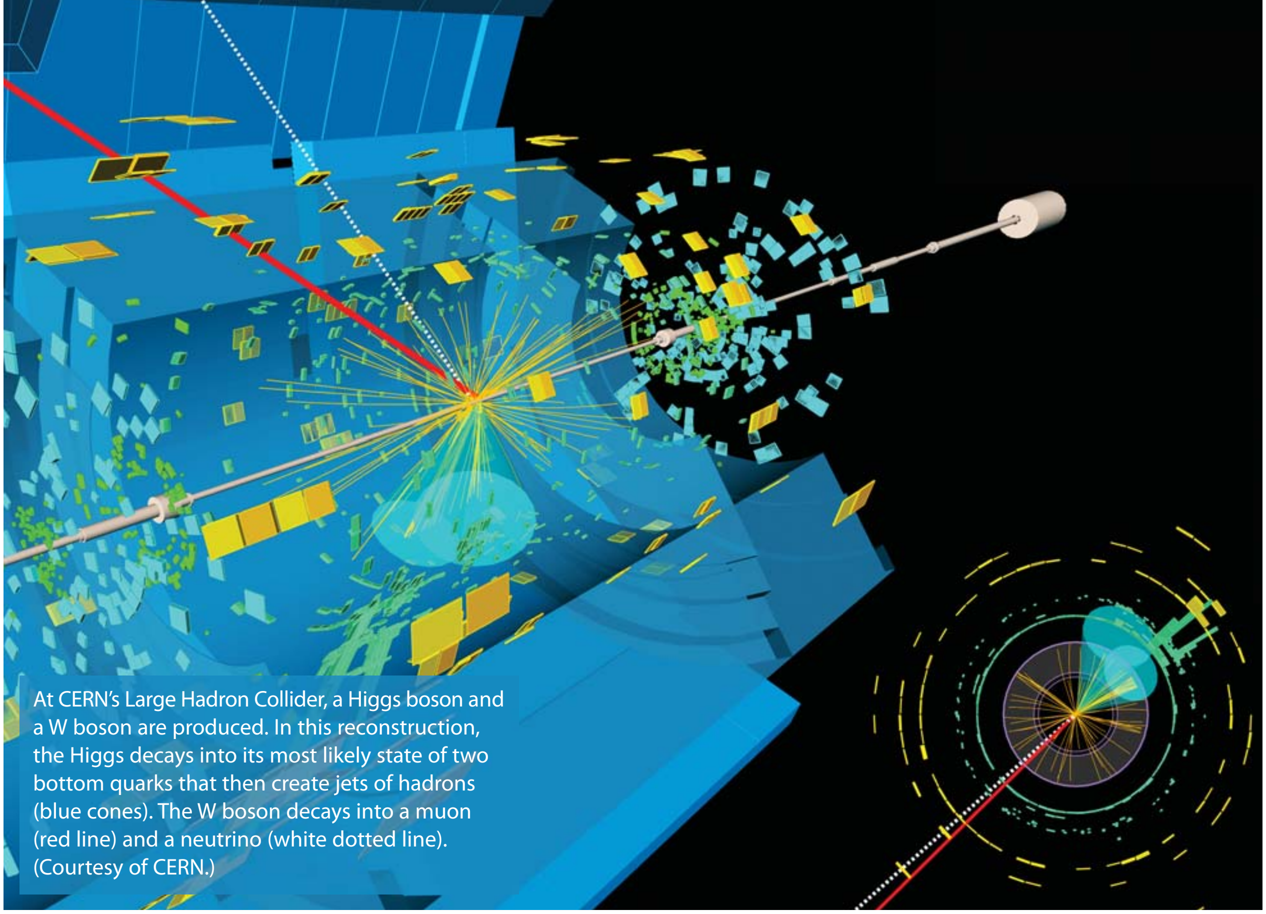

At CERN's Large Hadron Collider, a Higgs boson and a W boson are produced. In this reconstruction, the Higgs decays into its most likely state of two bottom quarks that then create jets of hadrons (blue cones). The W boson decays into a muon (red line) and a neutrino (white dotted line). (Courtesy of CERN.)



# Experimental basis of the standard model

Paul Grannis and Vera Lüth

**Understanding the subatomic particles and the interactions among them required the development of ever more sophisticated experiments—from early cloud chambers to huge, multielement detectors.**

Particle physics evolved from its roots in cosmic-ray and nuclear physics when scientists realized that there are more fundamental constituents of matter than just protons and neutrons. Over many years, increasingly sophisticated experiments provided the information needed to develop the underlying theoretical concepts. Although the primary experimental results on which the emerging standard model (SM) was built were published elsewhere, *Reviews of Modern Physics* has been pivotal in putting them into context.

## Broken symmetries in the weak interaction

Symmetries have been central to the development of the SM. The demonstration that weak-interaction decays are not invariant under spatial reflection[1] showed that they violate parity symmetry. More surprisingly, the combined operation of matter–antimatter interchange (*C*) and spatial reflection (*P*) was found to be violated in neutral kaon decays[2] at the 0.1% level. There was no explanation for that effect until it was recognized in 1973 that a model with three generations of quark pairs would also allow for *CP* violation in decays of neutral B mesons,[2] which was observed in 2001. The similarity between the weak and

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electromagnetic interactions, and the observed short range and parity violation of the weak interaction, implied the existence of massive, spin-1, force-carrying bosons with both vector and axial-vector components. The $W^+$, $W^-$, and $Z^0$ bosons discovered[3] at the CERN proton–antiproton collider in 1983 verified that prediction.

The nonconservation of probability predicted in processes involving those bosons at high energy was ultimately "repaired" by the Higgs mechanism responsible for spontaneous symmetry breaking of a unified electromagnetic and weak interaction. The symmetry breaking provided the *raison d'être* for the observed massless photon and massive $W^+$, $W^-$, and $Z^0$ bosons and for the spin-0 Higgs boson discovered[4] in 2012.

The observation that neutrinos produced from the decay of a pion into a muon and a neutrino subsequently interact to produce muons but not electrons[5] was a surprise and meant that these neutrinos differ from those produced from nuclear beta decays. Another great surprise was the realization that neutrinos from the Sun[6] and from particle decays in atmospheric cosmic-ray showers[7] transform from one type to another. Those findings—and the discovery[8] of the $\tau$, the third charged lepton—revealed that there are three generations of charged lepton and neutrino pairs and that at least two of the neutrinos have nonzero mass.

## Revealing the strong interaction

The notion that mesons and baryons are composed of quarks was bolstered experimentally[9] in the early 1970s. Three quark flavors—up, down, and strange—were sufficient to explain the patterns of the known hadrons until 1974, when experiments at Brookhaven and SLAC revealed a new meson carrying a fourth quark flavor, charm.[10] Subsequent experiments at Fermilab found the even heavier bottom and top quarks[11] and thus established that, just as for the leptons, there are three generations of quark pairs.

The SM theory of the strong interactions was built on such observations as highly inelastic scattering of electrons and neutrinos from nucleons.[12] The scattering first revealed the nucleon's point-like constituents, thus supporting the quark picture, and subsequently showed the characteristic momentum-transfer dependence of their coupling to gluons—the mediators of the strong force—that is at the heart of quantum chromodynamics (QCD). Experiments verified calculations of many hadronic cross sections at high energy[13] and thereby established the validity of QCD as the theory of strong interactions.

Although the SM has by now been verified by thousands of measurements, it remains a mysterious success. For instance, it contains 26 *ad hoc* parameters—masses, mixing angles, couplings, and so on—that, if modified, would lead to an unrecognizably changed universe.[14] And although the SM edifice is well founded, it is manifestly incomplete!

## Tools and instruments

The pioneering measurements discussed here would not have been possible without the increasing sophistication and power of experimental tools.[15] Accelerators evolved from tabletop cyclotrons to colliders tens of kilometers in circumference. Instruments that measure particle reactions grew in size, complexity, and precision—from early cloud chambers to huge multielement electronic detectors. The revolution in computing greatly expanded the reach of experiments. And newly developed technologies have found applications in medicine, industry, national security, and other sciences.[16]

The rapidly expanding base of knowledge about the SM needed an evolving compendium of numerical information about the properties of the myriad particles and their interactions. *Reviews of Modern Physics* published frequent updates of such information, beginning with a 1964 article on particle properties.[17] In fact, the journal has served as an archive of the fundamental constants of our science since its first article, "Probable values of the general physical constants," was published.[18]

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