A More Precise Higgs-Boson Mass

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Teaser: A new value for the Higgs boson mass will allow stronger tests of the standard model and of theories about the universes stability.

A great insight of twentieth-century science is that symmetries expressed in the laws of nature need not be manifest in the outcomes of those laws. Consider the snowflake. Its structure is a consequence of electromagnetic interactions, which are identical from any direction, but a snowflake only looks the same when rotated by multiples of 60° about a single axis. The full symmetry is hidden by the particular conditions under which the water molecules crystallize. Similarly, a symmetry relates the electromagnetic and weak interactions in the standard model of particle physics, but we know it must be concealed because the weak interactions appear much weaker than electromagnetism. To learn what distinguishes electromagnetism from the weak interactions was an early goal of experiments at CERN's Large Hadron Collider (LHC). The ATLAS and CMS Collaborations gave a big part of the answer in mid-2012, when they announced the discovery of the Higgs boson in the study of proton–proton collisions [1]. Now the discovery teams have pooled their data analyses to produce a measurement of the Higgs-boson mass with 0.2% precision [2]. The new value enables physicists to make more stringent tests of the electroweak theory and of the Higgs boson's properties.

The electroweak theory [3] is a key element of the standard model of particle physics that weaves together ideas and observations from diverse areas of physics [4] In the theory, interactions are prescribed by gauge symmetries. If nature displayed these symmetries explicitly, the ensuing force particles would all be massless, whereas we know experimentally that the weak interactions must— because they are short-ranged—be mediated by massive particles. The so-called Higgs field was introduced to the electroweak theory to hide the gauge symmetry, leading to weak force particles ($W^{\pm}$ and Z^0) that have mass, and a massless photon.

The Higgs boson is a spin-zero excitation of the Higgs field and the footprint of the mechanism by which the electroweak gauge symmetry is hidden in the standard model. The Higgs boson's interactions are fully specified in terms of known couplings and masses of its decay products, but the theory does not predict its mass. Experimenters can measure the energies and momenta of decay products and determine the Higgs-boson mass using kinematical equations. Once that mass is known, the rates at which the Higgs boson decays into different particles can be predicted with high precision, and compared with experiment. For a mass in the neighborhood of 125 GeV, the electroweak theory foresees a happy circumstance in which several decay paths occur at large enough rates to be detected.

ATLAS and CMS are large, broad-acceptance detectors located in multistory caverns about 100 meters below ground [5]. In the discovery run of the LHC, the ATLAS and CMS Collaborations searched for decays of a Higgs boson into bottom-quark–antiquark pairs, tau-lepton pairs, and pairs of electroweak gauge bosons: two photons, W^+W^-, and Z^0Z^0. The actual discovery was based primarily on mass peaks associated with either the two-photon state or Z^0Z^0 pairs decaying to four leptons (electrons or muons). These channels, for which the ATLAS and CMS detectors have the best mass resolution, form the basis of the new report.

Both of the "high-resolution" final states are relatively rare: the standard model predicts that only about 1/4% of Higgs-boson decays produce two-photon states; the four-lepton rate is predicted to be nearly 20 times smaller. The two-photon channel exhibits a narrow resonance peak that contains several hundred events per experiment; the Z^0Z^0 to four-lepton channel yields only a few tens of signal events per experiment. The collaborations chose different detector technologies, and therefore different measurement and calibration methods [2]. These differences make pooling the data complicated, but also allow the experimentalists to cross-check systematic uncertainties in their separate measurements. Their combined analyses yield a Higgs boson mass of 125.09 ± 0.24 GeV, where the precision is limited by statistics and by uncertainties in the energy or momentum scale of their detectors.

The first consequence of the new, precise mass value is sharper predictions, within the standard model, for the relative probabilities of different Higgs-boson decay modes and production rates [6]. So far, the measured decay modes and production rates agree with standard-model predictions. The current uncertainties in the measured rates are large, but they will be narrowed in the coming runs at the LHC, and at possible future colliders. Evidence of any deviation would suggest that the Higgs boson does not follow the standard-model textbook, or that new particles or new forces are implicated in its decays.

With a precisely known Higgs-boson mass, M_H, theorists can make more refined predictions of the quantum corrections to many observables, such as the Z^0 decay rates. These predictions test the consistency of the electroweak theory as a quantum field theory. Figure 1 illustrates a telling example [7]. The diagonal blue ellipses show the values of the W-boson and top-quark masses required to reproduce a selection of electroweak observables, once M_H is fixed. (The narrow and wide ellipses represent 68% and 95% confidence levels, respectively.) The range of masses depends on M_H, and the precision with which it is known controls the width of the blue ellipses. The preferred range overlaps the green ellipses, which show the directly measured values of M_W and m_t. In the future, more precise values for the Higgs-boson mass, M_W, and m_t could unveil a discrepancy that might lead to the discovery of new physics.

The specific value of M_H constrains speculations about physics beyond the standard model, including supersymmetric or composite models. Perhaps most provocative of all is the possibility that the measured value of the mass is special. Quantum corrections influence not just the predictions for observable quantities, but also the shape of the Higgs potential that lies behind electroweak symmetry breaking in the standard model. According to recent analyses, the newly reported value of the Higgs boson mass corresponds to a near-critical situation in which the Higgs vacuum does not lie at the state of lowest energy, but in a metastable state close to a phase transition [8]. This might imply that our universe is living on borrowed time, or that the electroweak theory must be augmented in some way.
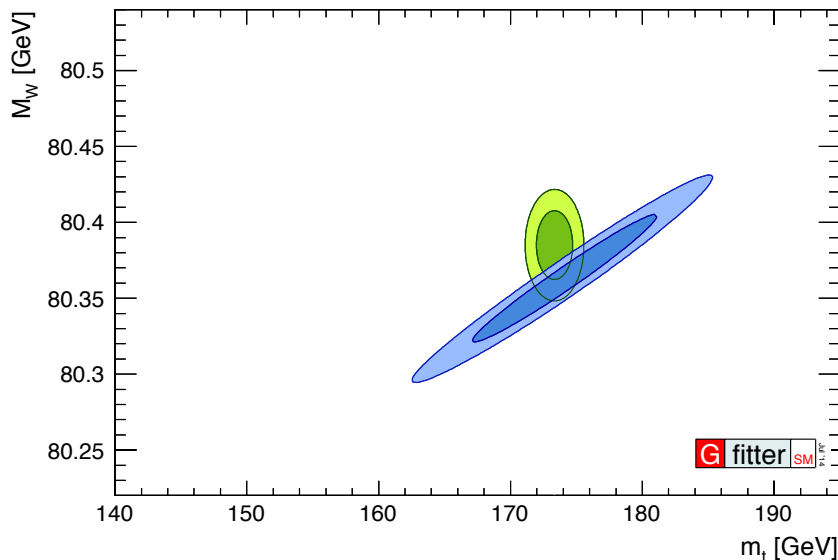
Figure 1: Inferred (blue) and measured (green) values of the top-quark and W-boson masses. The inner and outer ellipses represent 68% and 95% confidence levels for the measured and inferred values, respectively. Within current experimental and theoretical uncertainties, the two determinations agree. A more precise value of the Higgs mass would narrow the width of the blue ellipses, whereas improved measurements of M_W and m_t would shrink the green ellipses, making for a more incisive test for new physics. (Note, the calculations assume the central value of the Higgs mass is 125.14 GeV, which differs insignificantly from the new measurement by ATLAS and CMS, and does not affect the width of the blue ellipses.) [Credit: The Gfitter Group, Ref. [7]]

With LHC Run 2 about to commence, now at higher energies, we look forward to a new round of exploration, searches for new phenomena, and refined measurements. Combined analyses and critical evaluations, such as the measurement of the Higgs-boson mass discussed here, will help make the most of the data. We have much still to learn about the Higgs boson, the electroweak theory, and beyond.

Acknowledgements

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About the Author

CHRIS QUIGG is Senior Scientist at the Fermi National Accelerator Laboratory. His research spans many topics in particle physics, from heavy quarks through cosmic neutrinos. His work on electroweak symmetry breaking and supercollider physics, which was recognized by the 2011 J. J. Sakurai Prize of the American Physical Society for outstanding achievement in particle theory, charted the course for exploration at Fermilab's Tevatron and CERN's Large Hadron Collider. His current research centers on experiments at the LHC. A new edition of his classic textbook, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions,* has been published by Princeton University Press.