Physics

VIEWPOINT

Sizing Up the Top Quark's Interaction with the Higgs

A proton collision experiment at CERN provides a new handle on the Higgs boson's interaction with the heaviest of the quarks.

by Matthew Reece*

Among the most recently discovered elementary particles, the top quark and the Higgs boson may be our best bets to reach a deeper understanding of the laws of nature. That's because both particles are outliers in the particle zoo. The top quark is similar to the up quark found in ordinary matter, but it is about one hundred thousand times heavier—with a mass close to that of a tungsten nucleus. The Higgs boson, meanwhile, is the only fundamental particle observed so far that doesn't have the intrinsic property of spin. This attribute is essential to the Higgs boson's role in the standard model, where it is tied to the mechanism that endows elementary particles with mass. The Compact Muon Solenoid (CMS) Collaboration at CERN's Large Hadron Collider (LHC) now provides the most definitive measurement to date of the strength of the interaction between the Higgs boson and the top quark [1]. The measured value of this important parameter agrees with the standard model prediction. But the relatively large uncertainty (13%) leaves the door open to future measurements uncovering a discrepancy, which could lead to the resolution of mysteries surrounding the Higgs mechanism.

Six years after it was first detected, physicists are still subjecting the Higgs boson to experimental scrutiny. The particle is an excitation of the so-called Higgs field, which permeates spacetime and interacts with elementary particles like the electron and quarks, thereby giving them mass. But the microscopic mechanism that causes the Higgs field to fill spacetime is somewhat of a mystery. One idea is that the field arose from some sort of fundamental particle interaction, analogous to the pairing interaction between electrons in a metal that leads to superconductivity. Several proposed theories related to this idea depend on the interaction between the Higgs boson and the top quark, and measuring the interaction strength would allow a test of these models. The top-Higgs interaction strength also underlies the so-called fine-tuning puzzle in the theory of the weak interaction. This enigma relates to a discrepancy between the actual mass of the Higgs boson and its expected value if one takes into account quantum corrections. Finding a top-Higgs interaction strength that differs from its expected value could provide a clue as to how to resolve this discrepancy.

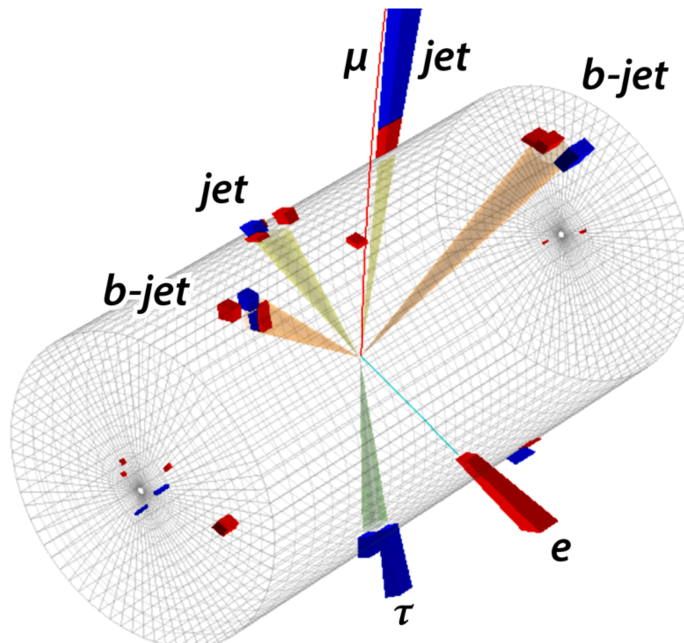

Figure 1: CMS determined the strength of the interaction between the top quark and the Higgs boson by analyzing the rate at which proton-proton collisions produce a Higgs boson and a pair of top quarks [1]. This so-called $t\bar{t}H$ process produces a shower of other particles whose energy is deposited into the CMS calorimeters at the spots indicated by the red and blue rectangles. The event shown here includes an electron (*e*), a muon (μ), a tau lepton (τ), and multiple jets, some of which originate from bottom quarks (b). Because the top quark and the Higgs boson are so massive, a $t\bar{t}H$ event can produce every type of particle detectable at the LHC. (CERN/CMS)

Because of its huge mass, the top quark's interaction with the Higgs boson was expected to be much stronger than that of the other quarks. There are various ways to measure the

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interaction strength, but the CMS approach is considered the "cleanest": They look for proton-proton collisions that produce a Higgs boson in association with a top quark and an antitop quark, otherwise known as the $t\bar{t}H$ process. The rate of this process gives a direct measure of the top-Higgs interaction strength, and theorists have long advocated for studying this process to gain insight into Higgs physics [2, 3].

The CMS measurement is a *tour de force*. First, the $t\bar{t}H$ process is relatively rare: Fewer than one in a thousand top-quark pairs come with Higgs bosons [4, 5]. Second, top quarks and Higgs bosons are never directly detected because they decay too rapidly. The experimentalists therefore looked for the particles' decay products—a combination of quarks, leptons, and photons that must be identified and distinguished from a "background" of the same particles produced in other ways. To have confidence that these signals corresponded to the $t\bar{t}H$ process, the CMS researchers analyzed multiple ways in which the two top quarks and the Higgs boson could decay (Fig. 1). For example, one sub-analysis searched for the $t\bar{t}H$ process when the Higgs boson decays to a pair of bottom quarks and the decay of the top-quark pair produces at least one electron or muon [6]. The researchers relied on an arsenal of modern machine-learning tools and more traditional methods to discriminate the signal from the background.

In assessing the statistical significance of the signal, the researchers had to account for a number of experimental and theoretical uncertainties. These included the distribution of quarks and gluons inside the proton and the expected rate of top quark production, as well as the energy calibration of the CMS detector. CMS combined a large set of case-by-case analyses to obtain evidence for the $t\bar{t}H$ process above background at the "5-sigma" level of statistical significance—the gold standard for particle physics. This result improves on the 4.2-sigma significance of the evidence from an earlier analysis by ATLAS [7], another CERN experiment.

CMS's measurement confirms that the Higgs boson interacts with the top quark approximately as strongly as predicted by the standard model. Hints of this agreement had already appeared in earlier LHC experiments that measured the rate of production of Higgs bosons when two gluons fuse inside colliding protons. This quantum process is mediated by virtual top quarks, and if the top-Higgs interaction were very different from its standard model value (say zero), the gluon-fusion experiments would not have seen as many Higgs bosons as they did. But because gluon fusion involves the top quark only indirectly, there was always the possibility that this agreement was accidental, a result of some other unknown quantum effect that altered the gluon fusion. The CMS measurement eliminates this possibility, but it has a large enough uncertainty to allow for other kinds of new physics.

The CMS measurement of the $t\bar{t}H$ process solidifies a major element of the standard model. But another key piece remains completely unconstrained: the Higgs boson's interaction with itself. The strength of such an interaction could provide an important clue to the nature of the electroweak phase transition, the time in the early Universe when the Higgs field acquired a nonzero value and the W and Z bosons became massive. Pinning down this interaction would require collisions that produce multiple Higgs bosons at a higher rate than the LHC can achieve at its operating energy. Either a 1-TeV lepton collider or a 100-TeV proton-proton collider would allow researchers to obtain the Higgs boson's self-interaction with less than 10% uncertainty—accurate enough to distinguish between models of the electroweak phase transition [8, 9]. With such machines, the uncertainty in the $t\bar{t}H$ measurement could also be reduced to around a percent. Having learned that the Higgs boson exists and that it approximately fits its description in the standard model, we are now intensely curious to know more about it.

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