The TOP QUARK, 20 years after its discovery

Dmitri Denisov and Costas Vellidis

The heaviest of nature's elementary particles plays an outsized role in many fundamental processes. But because the top quark is so massive, it eluded experimental detection for nearly two decades.

Ever since the days of the Greek philosophers, humankind has sought to identify the elementary building blocks of matter. Over time, the notion has been refined; the original idea that indivisible atoms were the fundamental elements has evolved to the present view that objects called quarks lie at the heart of all matter. So in 1995 the discovery at Fermilab of the top quark—the sixth and possibly last of the quarks—might have been thought to signal the end of one of science's longest searches.[1]

But the properties of the top quark are bizarre and raise new questions. In particular, its mass is the largest of any known elementary particle. That weightiness suggests the top quark plays a fundamental role in the breaking of the symmetry of the electroweak interaction, a symmetry that requires that the masses of the elementary particles vanish. If so, the top quark is itself fundamental to the generation of mass.

A missing family member

In 1964 Murray Gell-Mann and George Zweig independently proposed the quark hypothesis[2] to account for the explosion of subatomic particles discovered in accelerator and cosmic-ray experiments during the 1950s and early 1960s. More than 100 new particles had been observed, most of them strongly interacting and very short-lived. Those strongly interacting particles, called hadrons, are not elementary; they possess a definite size and internal structure. The quark hypothesis suggested that different combinations of three quarks—the up (u), down (d), and strange (s) quarks—and their antiparticles could account for all the hadrons then known. Each quark had an intrinsic spin of $\frac{1}{2}\hbar$ and was presumed to be elementary. To explain the observed spectrum of hadrons, quarks had to have electric charges that are fractions of the electron charge.

Quarks seemed to form a counterpart to the other class of elementary particles: the leptons, which then included the electron (e) and muon (μ) and their companion chargeless neutrinos, ν_e and ν_μ. The leptons do not feel the strong interaction that holds nuclei together, but they do participate in the electromagnetic interaction and the weak interaction responsible for radioactive decays. They have the same spin as the quarks and, like them, have no discernible size or internal structure.

By the mid 1970s, quarks had been incorporated into the now standard model of particle physics. But initially, most physicists were reluctant to accept that quarks were anything more than convenient abstractions aiding particle classification. The fractional electric charges seemed bizarre, and experiments repeatedly failed to turn up any individual free quarks (for a personal recollection of the times, see the article by O. W. Greenberg, PHYSICS TODAY, January 2015, page 33). But two developments during the 1970s established the reality of quarks. Fixed-target experiments with high-energy leptons directed at protons and neutrons showed that the target hadrons contain point-like internal constituents. And in 1974, physicists at Brookhaven

Dmitri Denisov and **Costas Vellidis** are researchers at the Fermi National Accelerator Laboratory in Batavia, Illinois. Each serves as a co-spokesperson for one of the two experiments that discovered the top quark. Denisov represents the D0 collaboration; Vellidis, the Collider Detector at Fermilab collaboration.

The Tevatron ring (upper right) and the main injector ring stand out in this aerial view of Fermilab.

COURTESY OF FERMILAB

National Laboratory and SLAC discovered a striking hadron with a mass of 3.1 GeV; the particle was a bound state of a new quark called charm (c) and its antiquark. Now that particle physicists had identified two quarks of each possible charge, they could establish a symmetry relating the quark pairs (u, d) and (c, s) to the lepton pairs (e, ν_e) and (μ, ν_μ).

New discoveries quickly and unexpectedly broke that symmetry. In 1976, experiments at SLAC turned up a third charged lepton, the tau. A year later scientists at Fermilab discovered a new hadron with a mass of about 10 GeV; they soon determined it to be a quark–antiquark bound state of yet another quark, the bottom (b).[3]

By 2000 the tau neutrino had been discovered at Fermilab, and physicists understood that the quarks and leptons represent two parallel but distinct classes of matter. Both quarks and leptons come in three generations of paired elements with differing electric charge. But when the tau lepton was first found, the third-generation quark doublet seemed to be missing a member, whose existence and charge (⅔ the magnitude of the electron charge) were inferred from the existing pattern. In advance of its sighting, physicists named it the top (t) quark. Thus began a search that lasted for almost 20 years.

When you're a jet

Based on the ratios of the observed quark masses, physicists in the late 1970s suggested that the top quark would be about three times as heavy as the bottom quark; they thus expected that it would appear in a heavy new hadron containing a top–antitop pair and having a mass of about 30 GeV. The electron–positron colliders then under construction in Germany, the US, and Japan raced to capture the prize, but they found no hint of the top quark.

Progress in particle physics is intimately connected with the construction of more powerful accelerators. In the early 1980s, CERN introduced a new class of accelerator in which counterrotating beams of protons and antiprotons collided with an energy of about 300 GeV per beam. The protons and antiprotons brought their constituent quarks and antiquarks into collision with typical energies of 50 GeV to 100 GeV apiece, so the top-quark search could be extended considerably.

The CERN experiments led to the important discovery of the W and Z bosons, which act as carriers of the weak force. But they also demonstrated a new aspect of quarks: jet formation. Quarks had continued to elude direct detection even though they can be violently scattered in high-energy collisions. The high-energy quarks emerging from the interaction region are subject to the strong interaction, and as they leave, quark–antiquark pairs are created from the available collision energy. The quarks and antiquarks so created combine into the ordinary hadrons that the experiments detect. The particles formed by that hadronization process tend to cluster along the direction of the original quark trajectory and are thus recorded as a jet of nearly collinear particles.

With the advent of the CERN collider and, in 1988, Fermilab's even more powerful Tevatron proton–antiproton collider, with an energy of 900 GeV per beam, the search for the top quark turned to new avenues. For the large top-quark masses now accessible, theorists expected that top–antitop bound states would not have time to form; instead, experiments should produce isolated top quarks. If the top quark were less massive than the W boson, then W-boson decay into a top quark and a

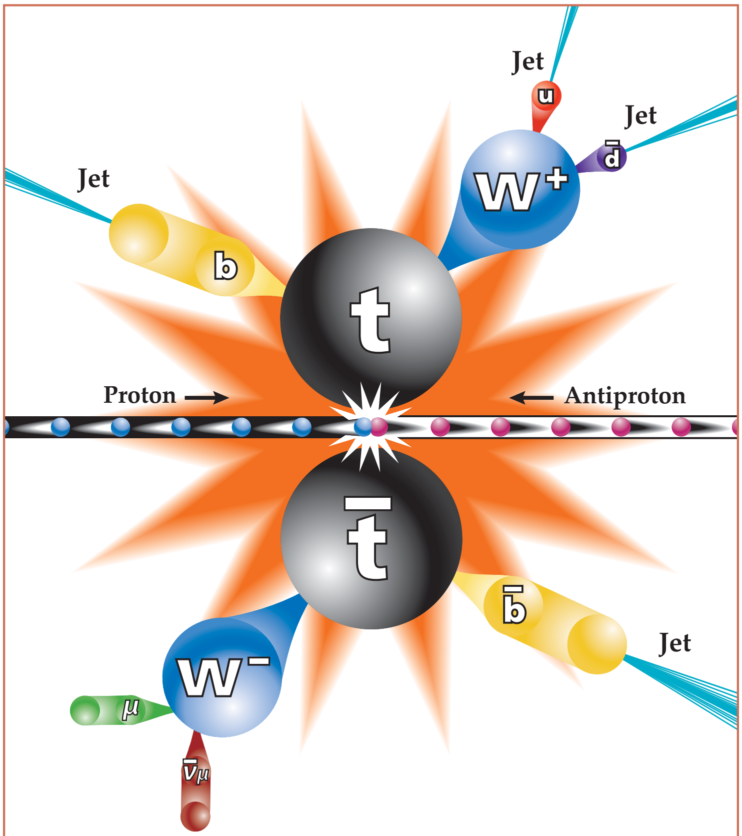


Figure 1. A top–antitop quark pair can be produced from the collision of energetic protons and antiprotons. A quark from the proton annihilates an antiquark from the antiproton, and according to the celebrated $E = mc^2$ formula, the energy E released by the annihilation can be converted into the mass m of new particles. The top quark (t) decays into a W boson and a bottom quark (b), and the antitop quark ($\bar{t}$) decays into the corresponding antiparticles. The W boson could decay into a pair of quarks that form jets, as described in the text, or it could decay into a charged lepton and a neutrino. In the process illustrated here, the top quark's final decay products are two jets associated with quarks arising from W boson decay and a single jet from a bottom quark; the antitop quark yields a muon, a neutrino, and a jet from a bottom quark. Note that the jets associated with bottom quarks contain particles that are displaced by a few millimeters from the location at which the bottom quark is created. (Courtesy of Fermilab.)

bottom quark could be the predominant mode of top-quark production. The UA1 experiment at CERN reported some indication of that process[4] in 1984, but the later CERN UA2 and Collider Detector at Fermilab (CDF) experiments ruled out that mechanism. By 1990 the CDF collaboration had established that the top quark was heavier than 91 GeV and thus eliminated the possibility that W bosons could decay to top quarks.

Top quarks heavier than 100 GeV are produced predominantly as top–antitop quark pairs. According to the standard model, the massive top quarks will decay almost exclusively into a W boson and a bottom quark, as will the accompanying antiquark. Each of the generated bottom quarks will hadronize into a jet. The W bosons can decay into a lepton and its associated neutrino or into a pair of quarks that subsequently turn into jets. Figure 1 shows a typical top-production event.

In 1992 the D0 collaboration joined the CDF collaboration at the Tevatron as a long run began. Figure 2 shows the two groups' detectors. The D0 detector was designed to recognize leptons and jets over as large a solid angle as possible. The CDF detector, by contrast, was built to detect short-lived particles that survive long enough to travel a millimeter or so from the interaction point and was particularly good at sensing the bottom-quark jets characteristic of top-quark decay. Thus, although they searched for the same basic decay sequence, the two experiments had complementary approaches.

The race ends in a draw

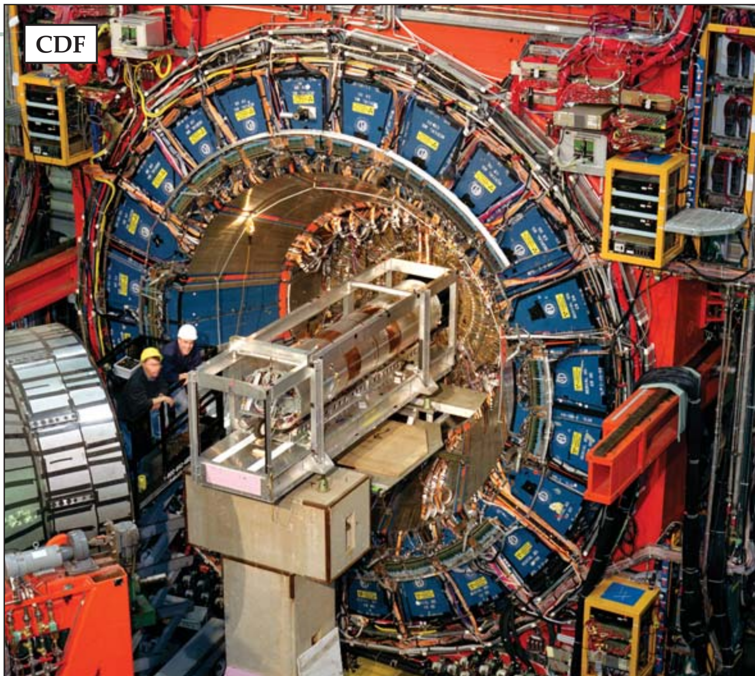
The Tevatron run that started in 1992 continued until 1996. During that time the CDF and D0 collaborations raced to discover the top quark. In 1994 the D0 team established that the top-quark mass is greater than 131 GeV. Later that year CDF researchers claimed the first evidence of top-quark production.[5]

But until the summer of 1994, the intensity of the Tevatron was disappointing. The collider included seven separate accelerators and a complex web of connecting beamlines that extended over many miles. Many technical gymnastics were required to accelerate protons, produce secondary beams of antiprotons, accumulate and store the intense antiproton beams, and, finally, inject the counterrotating beams of protons and antiprotons into the Tevatron for acceleration to 900 GeV. Fermilab accelerator physicists had poured an enormous amount of effort into understanding and tuning each separate element of the acceleration process. During a brief mid-1994 break, however, they discovered that one of the Tevatron magnets had been inadvertently rotated.

Once the problem was fixed, beam intensities doubled. With their accelerator now performing better, the physicists squeezed out an additional doubling of the event rate by early 1995. In no small part, the success of the CDF and D0 experiments in discovering the top quark rested on the superb achievements of the Fermilab staff. Their improvements to the Tevatron operation meant that the data samples accumulated in early 1995 were approximately three times as large as those used in previous analyses—and both the CDF and the D0 collaborations were poised to capitalize on the increase.

The CDF and D0 discovery papers were submitted to *Physical Review Letters* on 24 February 1995 and published back to back on 3 April of that year.[1] The two collaboration teams had scheduled a public joint seminar to be held at Fermilab on 2 March and had agreed that news of the discovery would not be made available to the physics community or news media until the day of the seminars. But word did get out. A few days before the seminars, "[a] *Los Angeles Times* reporter, K. C. Cole, called a distinguished Fermilab physicist to get an explanation of statistical evidence presented in the O.J. Simpson trial. The physicist used, as an illustration, 'the recent statistical evidence on the top quark from CDF and D0,' and Cole swiftly picked up the chase."[6]

In their paper, the CDF researchers concluded that the odds were only one in a million that background fluctuations could account for the events attributed to the production and decay of top quarks;



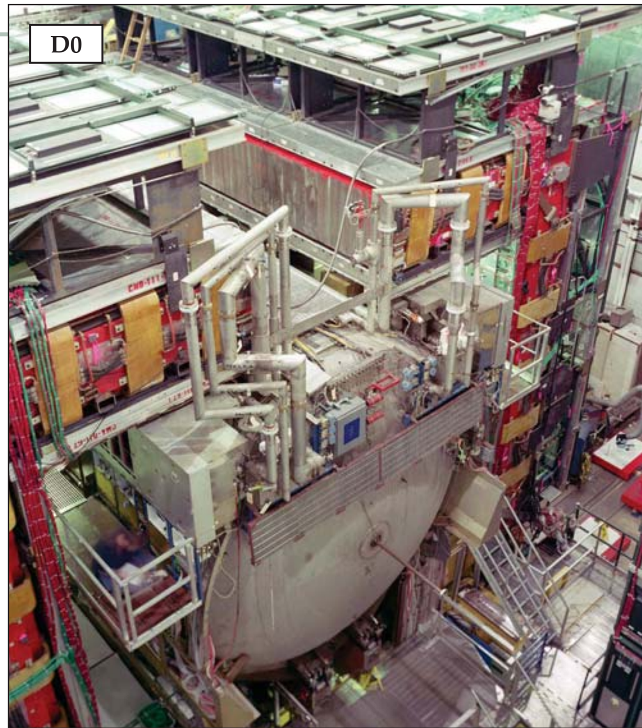


Figure 2. Large, complex detectors are needed to spot the products of top-quark decays. These detectors—the Collider Detector at Fermilab (CDF) on the left and the D0 on the right—weigh thousands of tons and contain millions of channels sensitive to tens of millions of interactions per second. The enormous amount of data coming from such detectors required the most modern computing and analysis tools and significant people power, too: Hundreds of scientists worldwide analyzed CDF and D0 data to come up with new discoveries and precision measurements of such elementary-particle parameters as the mass of the top quark. Some 26 countries are represented by the scientists who designed and operated these detectors or analyzed their data. (Courtesy of Fermilab.)

the D0 collaboration, in its paper, put the odds at two in a million. The top-quark masses reported by the two experiments were 176 ± 13 GeV for the CDF and 199 ± 30 GeV for the D0. Figure 3 shows the data from which those determinations were made and also includes more recent results from the 2001–11 Tevatron run.

The top-quark production mechanism that enabled the D0 and CDF discoveries is not the only way in which top quarks can be formed at hadron colliders. The standard model also allows electroweak interactions to yield a single top quark.[7] The predicted cross section for single top-quark production is reasonably large—about half that for top–antitop pair production—but the signal-to-background ratio is much worse. Thus physicists failed to observe single top-quark production until 2009, by which time the CDF and D0 teams had collected about 100 times the data[8] available in 1995.

A massive ambiguity

As data from the Tevatron's 2001–11 run continued to pour in, the CDF and D0 teams obtained increasingly precise measurements of such quark properties as electric charge, lifetime, and spin correlations. The collaborations also measured the production cross sections (essentially probabilities) of both top–antitop and single-top processes, and how those cross sections depended on different variables. Scientists have extensively sought for new physics in top-quark events—in particular, in tests of fundamental symmetries and searches for new particles coupled to top quarks. But most of the attention has been focused on obtaining the top-quark mass, a crucial property and the only one not predicted by theory. For one thing, together with the W-boson mass, it constrains the Higgs-boson mass, as shown in figure 4. Moreover, the large value of the top-quark mass indicates a strong coupling to the Higgs boson (see figure 5), so the top quark could provide special insights in our understanding of electroweak symmetry breaking.

The top-quark mass is, of course, extracted from experimental data yielded by events such as the one shown in figure 1. But the top quark is a strongly interacting particle, and different approximate treatments of the strong-force effects on the top-quark mass lead to slightly different determinations of its value. The CDF and D0 teams have developed many novel measurement techniques to both increase the precision of their observations and pin down the ambiguities related to the theoretical interpretation of those observations. Their combined results have yielded the most precise determination of the top-quark mass. In practice, the new techniques are applied to top–antitop quark production, for which the background is more manageable. They all take as a starting point that when the quark decays, it transfers its kinematic characteristics to a W boson and bottom quark; the measured energies and momenta of the final-state particles are used to reconstruct the top-quark mass.

That reconstruction is easier said than done. For example, the neutrinos produced in top-quark decays are not detected, and thus their momenta are not measured. Instead, the momenta are inferred from the decay kinematics, by constraining the mass of the charged-lepton-plus-neutrino system to be the precisely known mass of the W boson. Another difficulty is to correctly relate the experimentally

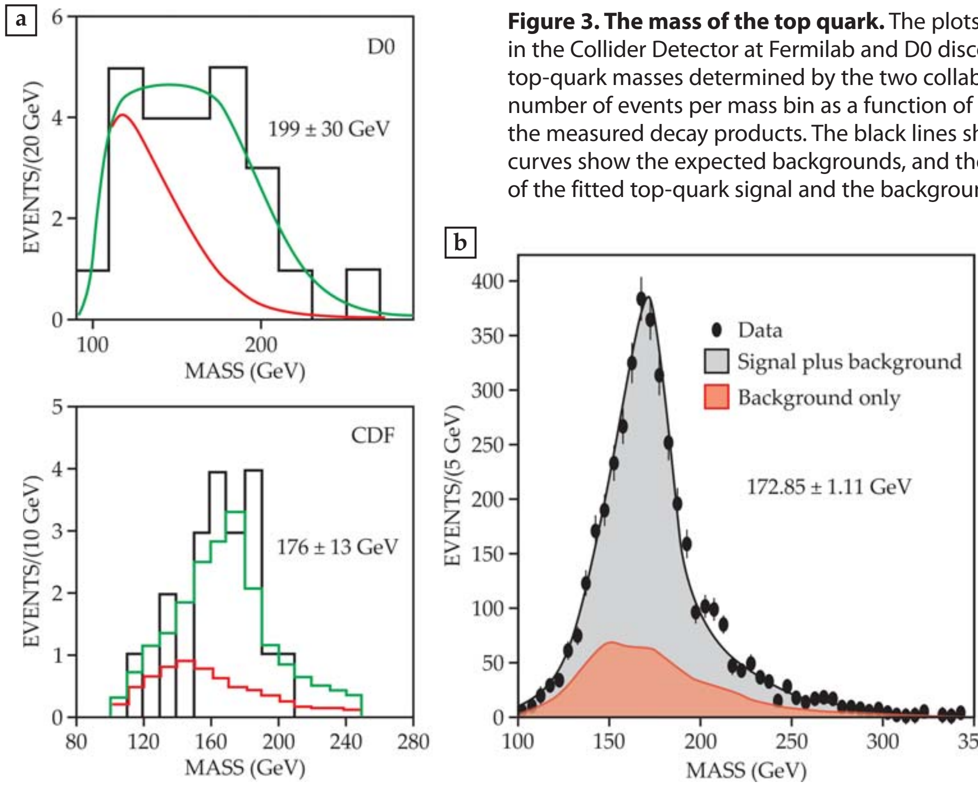


Figure 3. The mass of the top quark. The plots in **(a)** show the data presented in the Collider Detector at Fermilab and D0 discovery papers[1] of 1995 and the top-quark masses determined by the two collaborations. Each indicates the number of events per mass bin as a function of the mass of the object yielding the measured decay products. The black lines show the observations, red curves show the expected backgrounds, and the green curves show the sums of the fitted top-quark signal and the backgrounds. Both experimental groups interpreted the clear excess of signal over background as coming from the top quark. The mutual consistency of the experiments served as important evidence for the existence of a new quark. (Adapted from ref. 6.) **(b)** Results from the 2001–11 Tevatron run reflect a hundredfold increase in data available since the top-quark discovery. The indicated value of the top-quark mass is precise to better than 1%. (Courtesy of the CDF and D0 collaborations.)

reconstructed jets and final-state charged-particle trajectories to the quarks and leptons arising from the decays of the top quark and W boson.

To account for such ambiguities, CDF and D0 scientists have simulated top-quark pair production and decay together with the response of their detectors to the final-state particles. The price is the systematic uncertainties introduced by the simulation model. The challenge of the top-quark mass measurement is to reduce those systematic uncertainties and additional uncertainties arising from finite detector resolution. For example, the relatively low precision of jet-energy measurements can be improved by requiring that the mass of the jet pair from the W-boson decay be the mass of the W boson itself—a method known as the *in situ* calibration of the jet energy.

Another endeavor that has attracted much attention is the search for particles heavier than the top quark that decay into top–antitop pairs. Such particles might reveal themselves in resonances, or sharp peaks, in the mass spectrum of the top–antitop system. The hypothetical superheavy particles could interact predominantly with the top quarks either by a modified strong force, such as carried by putative massive gluons called axigluons, or by a modified weak force associated with heavy bosons. Thus observation of a top–antitop resonance would signal forces beyond those present in the standard model. The CDF and D0 collaborations have excluded such resonances for top–antitop masses of less than about 1000 GeV.

In 2010 the Large Hadron Collider (LHC) at CERN produced its first top quarks. Compared with

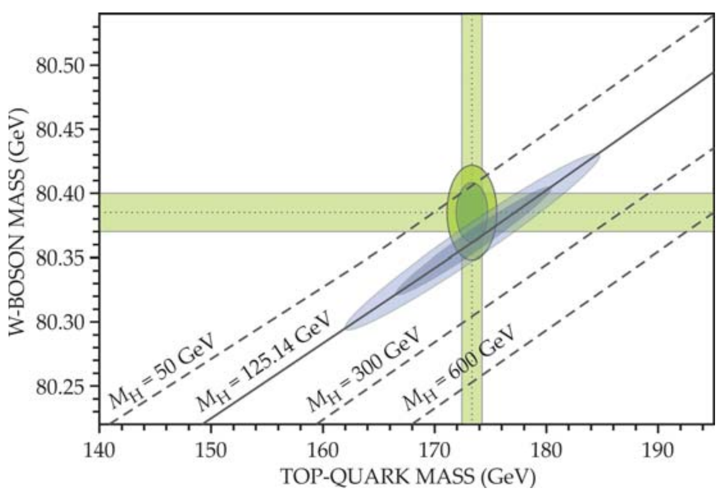


Figure 4. The masses of the top quark, W boson, and Higgs boson are related by the standard model. In this plot, the diagonal gray lines indicate the predicted value of the Higgs mass, given those of the W boson and top quark and various electroweak parameters. The horizontal and vertical bands indicate the 1-σ confidence regions of the measured W-boson and top-quark masses; the oval green contours cover 1-σ and 2-σ confidence areas for the joint W-boson and top-quark masses. The blue contours are 1-σ and 2-σ confidence areas for the W-boson and top-quark masses as predicted from electroweak parameters and the measured mass of the Higgs boson. The remarkable agreement between the experimental measurements and the predictions indicates a profound self-consistency of the standard model. (Adapted from an image courtesy of the Gfitter group, http://project-gfitter.web.cern.ch/project-gfitter.)

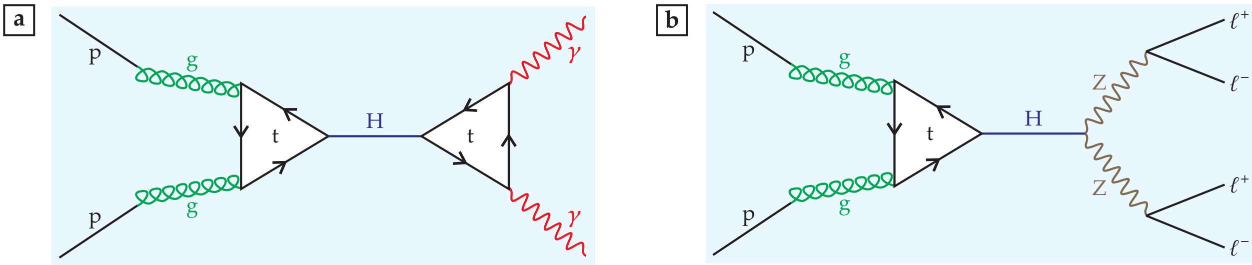


Figure 5. The Higgs boson couples to mass, so the strongest coupling is to the heaviest particle—the top quark. The strength of that coupling gives rise to the Higgs boson's dominant production mode, so-called gluon fusion in which two gluons (carriers of the strong force) from the colliding protons at the Large Hadron Collider (LHC) generate a top-quark loop, which then couples to a Higgs boson. The Higgs boson can decay **(a)** into two massless photons, again predominantly through a top-quark loop, or **(b)** into two massive Z bosons that subsequently can decay into leptons (electrons or muons, symbolized by ℓ). The two production and decay modes, with their easily identified final states, were the ones that revealed the Higgs boson at the LHC.[9] The observed agreement between their measured and predicted rates confirmed the presumed strength of the Higgs boson coupling to the top quark and thus supports the electroweak symmetry-breaking mechanism described by the standard model.

the Tevatron, the LHC operates at a higher collision energy, and it achieves greater beam intensity because it collides protons against protons rather than against antiprotons. As a result, the LHC has a higher rate of top–antitop pair production, and experiments there are advancing the methods developed at the Tevatron for precision measurements of top-quark properties and searches for new phenomena involving top quarks. For example, searches in the top–antitop mass spectrum at the LHC currently exclude any resonances with masses of up to about 2000 GeV.

Tevatron and LHC scientists have pooled their data to obtain the most up-to-date value of the top-quark mass. Their joint value of 173.34 ± 0.76 GeV has a precision of 0.4%—the best of any quark-mass measurement and only achievable because the top quark decays before it has time to form more-complex particles. As far as we can tell, the top quark is a point-like particle; it has no discernable internal structure. Its properties are very similar to those of the up and charm quarks, except for its short lifetime of 5×10^{-25} s and its remarkably large mass—some 200 times that of the proton, 40 times that of the bottom quark, and roughly equal to that of a gold nucleus. Surely, the top quark's striking obesity holds an important clue about how mass originates.

A metastable universe?

On 4 July 2012, the ATLAS and CMS collaborations at the LHC announced the discovery of the Higgs boson, along with the top-quark discovery, a milestone event in particle physics (see reference 9 and the article by Joe Lykken and Maria Spiropulu, PHYSICS TODAY, December 2013, page 28). For years, the hunt for the Higgs boson had been informed by constraints of its mass, which, as shown in figure 4, can be derived from the top-quark and W-boson masses. The Higgs-boson mass, 125.15 ± 0.24 GeV, together with the top-quark mass and the strength parameter of the strong interaction, turns out to be a key parameter for scientists investigating possible new physics at the so-called Planck scale of 10^{19} GeV. At such energies—much higher than those currently reachable by accelerators—quantum effects become important in gravity. And we know the standard model is not the final answer; some new physics must exist to explain neutrino masses, neutrino mixings, and dark matter, which makes up $5/6$ of all the matter in the universe but is subject to no known interaction other than gravity.

The measured Higgs-boson and top-quark masses indicate a particularly intriguing behavior for the Higgs potential. The potential, a function of the Higgs field, depends on two terms: One determines the Higgs-boson mass, and the other is a self-interaction term that is sensitive to the value of the top-quark mass. For some combinations of top-quark and Higgs-boson masses, as shown in figure 6, the potential minimum in which the Higgs field currently sits is not the absolute minimum of the potential, and quantum tunneling to a lower-energy state is permitted. In such cases, particle physicists speak of the metastability of the electroweak vacuum; the universe is in a state that may endure for a very long time, but not forever. The Higgs field may have been primordially trapped at that metastable minimum; if so, it may be responsible for another subtlety of the universe that seems to be indicated

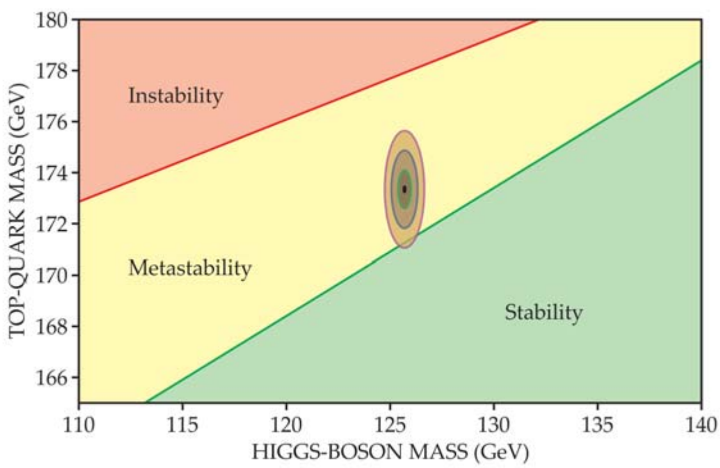


Figure 6. The universe is metastable, long-lived but not eternal, for certain combinations of top-quark and Higgs-boson masses. Given the current determination of the top-quark mass, the Higgs-boson mass of about 125 GeV is close to the boundary for stability, but a definitive answer will require a much more precise measurement of the top-quark mass. The three ellipses represent 1-σ, 2-σ, and 3-σ confidence areas for the mass determinations. (Adapted from ref. 10, which uses a somewhat different Higgs-boson mass than we cited in the main text.)

by astronomical data: cosmic inflation, a sudden expansion of space in the infancy of the universe (see the article by John Carlstrom, Tom Crawford, and Lloyd Knox, PHYSICS TODAY, March 2015, page 28).

Since vacuum metastability strongly and subtly depends on the mass of the top quark, it is not surprising that theoretical physicists disagree in their interpretations of experimental results, with some favoring and others disfavoring metastability. Unfortunately, systematic and theoretical uncertainties limit the precision of top-quark mass measurements obtained at hadron colliders. To improve the measurement precision, the community will need an electron–positron collider capable of producing top quarks. Such a collider, currently under consideration, could be able to discriminate between vacuum stability and metastability.

Some 20 years after the standard model was formulated, scientists at Fermilab's Tevatron accelerator discovered the top quark and completed the roster of fundamental constituents of matter in the standard model. The CDF and D0 experiments extensively studied the properties of the new quark and its interactions with other particles, and they used top-quark production and decays to test fundamental symmetries of the standard model and set sensitive exclusion limits on new physics. The precision measurements achieved at the Tevatron have, over the years, driven theoretical advances in top-quark physics.

The detection of the top quark and the exploration of its properties represent the pinnacle of the Tevatron legacy. Now the torch has been passed to the LHC. The top-quark studies there, and perhaps at a future electron–positron collider, may serve as a gateway to new and exciting discoveries.

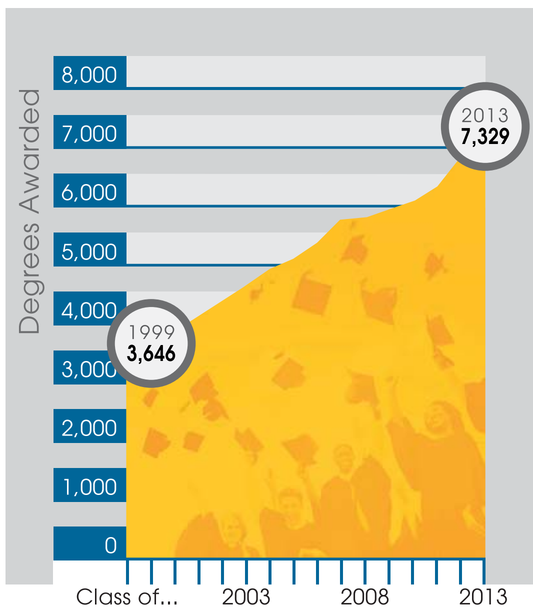
We acknowledge the staffs at Fermilab and the CDF and D0 collaborations for their role in the discovery of the top quark.

References

1. F. Abe et al. (CDF collaboration), *Phys. Rev. Lett.* **74**, 2626 (1995); S. Abachi et al. (D0 collaboration), *Phys. Rev. Lett.* **74**, 2632 (1995).
2. M. Gell-Mann, *Phys. Lett.* **8**, 214 (1964); G. Zweig, *An* SU_3 *Model for Strong Interaction Symmetry and Its Breaking*, 8182/TH.401, CERN (1964); *An* SU_3 *Model for Strong Interaction Symmetry and Its Breaking II*, 8419/TH.412, CERN (1964).
3. S. W. Herb et al., *Phys. Rev. Lett.* **39**, 252 (1977).
4. G. Arnison et al. (UA1 collaboration), *Phys. Lett. B* **147**, 493 (1984).
5. F. Abe et al. (CDF collaboration), *Phys. Rev. Lett.* **73**, 225 (1994).
6. For a pedagogical, firsthand account of the top-quark discovery, see B. Carithers, P. Grannis, *SLAC Beam Line* **25**(3), 4 (1995).
7. T. Stelzer, S. Willenbrock, *Phys. Lett. B* **357**, 125 (1995).
8. V. M. Abazov et al. (D0 collaboration), *Phys. Rev. Lett.* **103**, 092001 (2009); T. Aaltonen et al. (CDF collaboration), *Phys. Rev. Lett.* **103**, 092002 (2009).
9. G. Aad et al. (ATLAS collaboration), *Phys. Lett. B* **716**, 1 (2012); S. Chatrchyan et al. (CMS collaboration), *Phys. Lett. B* **716**, 30 (2012).
10. V. Branchina, E. Messina, A. Platania, *J. High Energy Phys.* **2014**(09), 182 (2014). ■

FACTOID

The number of physics bachelor's degrees awarded in the USA **has doubled** since 1999.



AIP Statistical Research Center

aip.org/statistics
stats@aip.org