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The Top Quark, Twenty Years On

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The elementary building blocks of matter have been sought ever since the days of the Greek philosophers. Over time, the quest has been refined from the original notion of indivisible "atoms" as the fundamental elements to the present idea that objects called quarks lie at the heart of all matter. So the discovery at Fermilab of the sixth–and possibly the last–of these quarks, the top quark, in 1995 [1, 2] might have been thought to signal end of one of our longest searches.

But the properties of this fundamental constituent of matter are bizarre and raise new questions. In particular, the mass of the top quark, the largest among all known particles, suggests that perhaps it plays a fundamental role in the breaking of the symmetry of the electroweak interaction, a symmetry which requires that the masses of the elementary particles are all vanishing, and thus in the question of how the mass of the particles arise.

In 1964 Murray Gell-Mann and George Zweig proposed the quark hypothesis to account for the explosion of subatomic particles discovered in accelerator and cosmic-ray experiments during the 1950s and early 1960s [3]. Over a hundred new particles, most of them strongly interacting and very short-lived, had been observed. These 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 of the particles then known. Each quark has an intrinsic spin of $1/2\ \hbar$ and is presumed to be elementary. To explain the observed spectrum of hadrons, quarks had to have electric charges that are fractions of the electron charge (see Fig. 1).

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

But most physicists were initially reluctant to believe 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. Two major developments established the reality of quarks during the 1970s. Fixed-target experiments directing high energy leptons at protons and neutrons showed that these hadrons contain point-like internal constituents. And in 1974 experiments at Brookhaven National Laboratory in New York and Stanford Linear Accelerator Center (SLAC) in California discovered a striking new hadron at a mass of 3.1 GeV. This particle was found to be a bound state of a new kind of quark, called charm or c, with its antiquark. With two quarks of each possible charge, a symmetry could be established between the quarks and the leptons. Two pairs of each were then known: (u,d) and (c,s) for quarks and (e,ν_e) and (μ,ν_μ) for leptons.

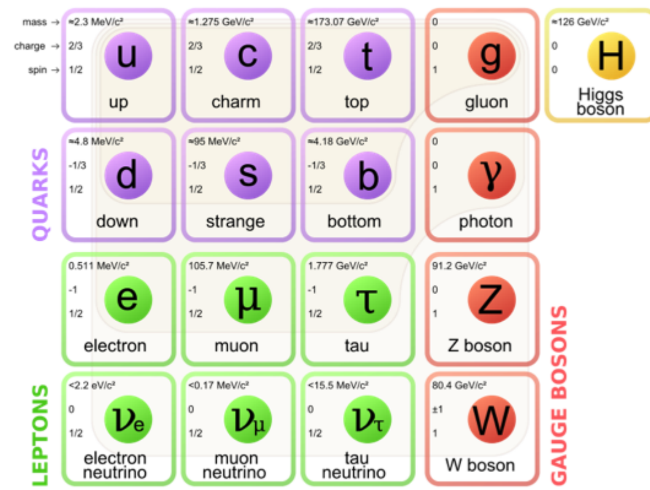

FIG. 1. The Standard Model table of elementary particles. Similar to the chemical periodic table (with substantially more elements), all currently known composite particles are made of quarks and leptons with forces exchanged by the force-carrying gauge bosons. The atom of hydrogen is made of a proton (a system of two u and one d quarks) and an electron revolving around the proton. Each particle has an antiparticle with the same mass and spin, but opposite electric charge. The positively charged π^+-meson is combination of a u quark and an anti-d quark. All of the above particles have no observed substructure down to distances of $\sim 10^{-18}$ cm. The Higgs boson is responsible for providing mass to quarks and leptons.

But this symmetry was quickly broken by unexpected discoveries. In 1976 experiments at SLAC turned up a third charged lepton, the tau. A year later at Fermilab in Illinois a new hadron was discovered, at a mass of about 10 GeV; it was soon found to be the bound state of yet another new quark–the bottom or b quark–and its antiparticle [4]. In 2000, the tau neutrino was also

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discovered at Fermilab.

With these discoveries, physicists understood that matter comes in two parallel but distinct classes–quarks and leptons (see Fig. 1). They occur in generations of two related pairs with differing electric charge. But the third-generation quark doublet seemed to be missing its charge +2/3 member, whose existence was inferred from the existing pattern. In advance of its sighting, physicists named it the top (t) quark. Thus began a search that lasted almost twenty years.

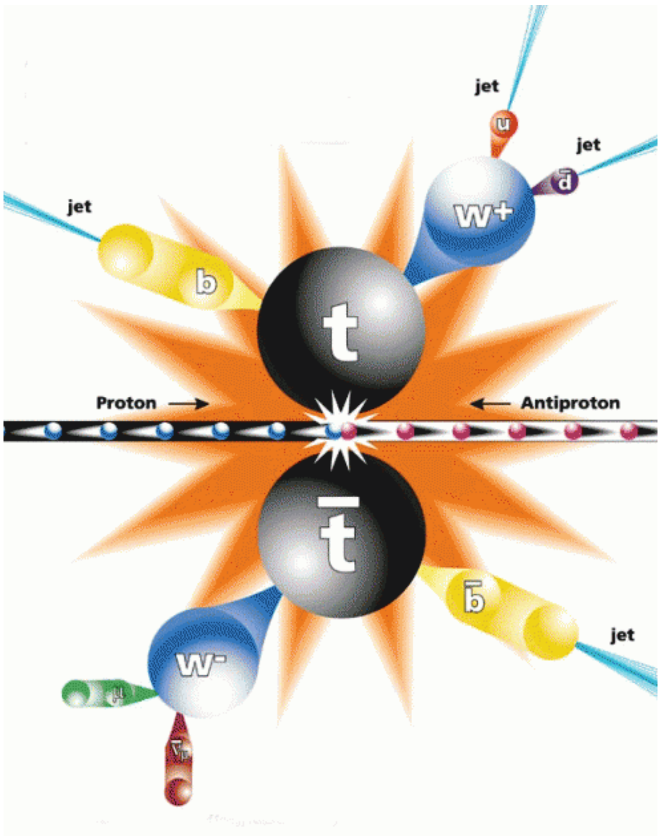

FIG. 2. Pairs of top and antitop quarks are produced from the annihilation of an incoming quark (from a proton) and antiquark (from an antiproton) by converting the energy of the colliding particles into mass according to the $E = mc^2$ formula. The top quark decays into W boson and a b quark. The W boson could decay into a pair of quarks (which "hadronize" into jets as described in the text) or into a charged lepton and a neutrino. b quarks are hadronizing into jets with characteristic decay vertex displaced by a few mm. In the figure, the top quark final decay products are two jets from quarks of the W boson decay and a jet from a b quark, while the antitop quark decays into a muon, a neutrino, and a jet from a b quark.

Using the ratios of the observed quark masses, physicists suggested that the t quark might be about three times as heavy as the b, and thus expected that the top quark would appear as a heavy new hadron containing a $t\bar{t}$ pair, at a mass around 30 GeV. The electron-positron colliders then under construction (PEP at SLAC, PETRA at DESY, Germany, and TRISTAN at KEK, Japan) raced to capture the prize, but they found no hint of the top quark.

In the early 1980s a new class of accelerator came into operation at CERN in Switzerland, in which counter-rotating 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 to 100 GeV, so the top quark search could be extended considerably. Besides the important discovery of the W and Z bosons that act as carriers of the electroweak force, the CERN experiments demonstrated another aspect of quarks. Though quarks had continued to elude direct detection, they can be violently scattered in high energy collisions. The high energy quarks emerging from the collision region are subject to the strong interaction as they leave the scene of the collision, creating additional quark-antiquark pairs from the available collision energy. The quarks and anti-quarks so created combine into ordinary hadrons that the experiments detect. These hadrons tend to cluster along the direction of the original quark, and are thus recorded as a "jet" of rather collinear particles.

With the advent of the CERN collider, and in 1988 the more powerful 1800 GeV proton-antiproton collider at Fermilab, the search for the top quark turned to new avenues, demonstrating that progress in particle physics is tightly connected with the construction of more powerful accelerators. In the large top quark mass range now accessible, the $t\bar{t}$ bound state was unlikely to have time to form and isolated top quarks were expected. For masses below mass of the W boson, W decay into a t quark and b quark could predominate. Some indication of this process was reported in 1984 by the CERN UA1 experiment [5], but it was later ruled out by the CERN UA2 and Fermilab CDF experiments. By 1990 CDF had extended the top mass limit to 91 GeV, thus eliminating the possibility for W to decay to top quark.

Top quarks heavier than 100 GeV are produced predominantly as top-antitop pairs. The Standard Model predicts that for such heavy mass the top quark decays almost exclusively into a W boson and a b quark, resulting in two W bosons and 2 b jets in each top-antitop pair event. The W boson itself decays into one lepton and its associated neutrino, or into a pair of quarks, which subsequently turn into jets (see Fig. 2).

In 1992, the D0 detector joined CDF as a long Tevatron run began (see Fig. 3). The design of the D0 detector stressed recognition of the leptons and jets over as large a solid angle as possible. Meanwhile CDF had installed a vertex detector of silicon microstrips near the beams intended to detect short-lived particles that survive long enough to travel a millimeter or so from the interaction point. This detector was particularly good at sensing the presence of the b-quark jets characteristic of top quark

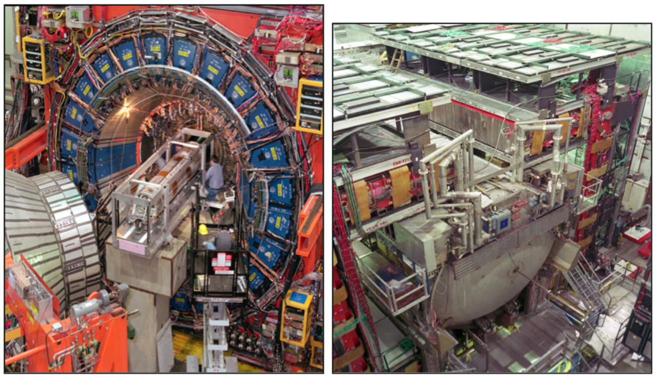

FIG. 3. Large and complex detectors are needed to detect the products of the top quarks decays. These detectors–CDF on the left and D0 on the right–weigh thousands or tons and contain millions of detector channels sensitive to 10's of millions of interactions per second. Scientists from 26 countries participated in the design, operation, and analysis of data taken with these detectors. The enormous amount of data coming from such detectors require ultra-modern computing and analysis tools, with 100's of scientists all over the world analyzing these data to come with new discoveries and precision measurements of the elementary particles parameters, such as the mass of the top quark.

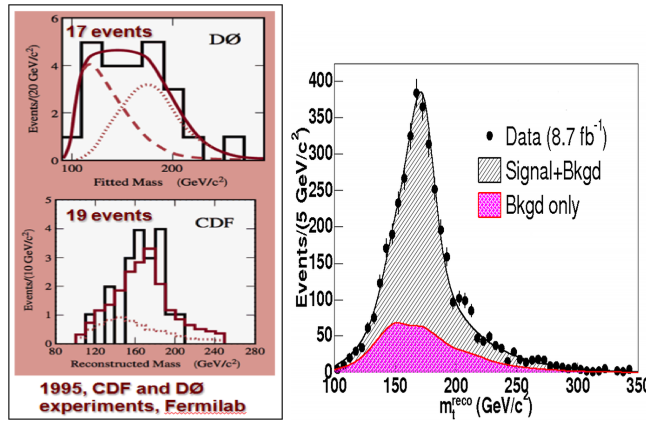

FIG. 4. On the left are plots from the original 1995 CDF and D0 discovery papers, indicating the number of events recorded vs. the mass of the object the decay products are coming from. The dashed lines peaking at lower masses show the expected backgrounds, the solid black lines show the observed events and the solid brown lines show the sums of the expected top quark signal and the backgrounds. There is a clear excess of signal over backgrounds, which was interpreted a top quark discovery by each experiment. The fact that both experiments confirmed each other served as an important evidence establishing the existence of the top quark. On the write is a similar plot from the 2001-2011 Tevatron run, indicating a two orders of magnitude increase in data available since the top quark discovery, which provided an opportunity for precise measurements of the top quark properties.

decay. Thus the two experiments, while searching for the same basic decay sequence, had rather complementary approaches.

The first long Tevatron run started in 1992 and continued until 1995. During this time the two experiments, CDF and D0, raced for the discovery of the top quark. In 1994, D0 set a new limit of top quark mass above 131 GeV. Later that year, CDF claimed first evidence for $t\bar{t}$ production [6]. But until summer 1994 the intensity of the collider was disappointing. The Tevatron involved a collection of seven separate accelerators with a complex web of connecting beam lines 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 counter-rotating beams of protons and antiprotons into the Tevatron for acceleration to 900 GeV each. Enormous effort had been poured into understanding and tuning each of the separate elements of the process. During a brief mid 1994 break, however, one of the Tevatron magnets was found to have been inadvertently rotated. With this problem fixed, beam intensities rose immediately by a factor of two. With the now improved performance of the accelerator, a further doubling of the event rate was accomplished by early 1995. In a very real sense, the success of CDF and D0 in discovering the top quark rested upon the superb achievements of the Fermilab accelerator complex. The improved operations meant that the data samples now accumulated were approximately three times larger than those used in the previous analyses, and both experiments were now poised to capitalize on the increase.

CDF and D0 "Observation" papers were submitted to *Physical Review Letters* on February 24 1995 and published on April 3, with public seminars scheduled at Fermilab for March 2. By agreement, the news of the discovery was not to be made available to the physics community or news media until the day of the seminars. In spite of all efforts, word did leak out a few days before. *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 illustration, "the recent statistical evidence on the top quark from CDF and D0," and Cole swiftly picked up the chase.

In its paper, CDF concluded that the odds were only one in a million that background fluctuations could account for events attributed to production and decay of top quarks. D0, in its paper, concluded that the odds were two in a million that these could have been caused by backgrounds. The top quark masses reported by the two experiments were 176 ± 13 GeV for CDF and 199 ± 30 GeV for D0 (see Fig. 4) [7].

The Standard Model predicts that top quarks are created via two independent production mechanisms at hadron colliders. The primary mode, in which a $t\bar{t}$ pair is produced via the strong interaction, was used by the D0 and CDF collaborations to discover the top quark.

The second production mode of top quarks at hadron colliders is the electroweak production of a single top quark [8]. The predicted cross section for single top quark production is about half that of $t\bar{t}$ pairs but the signal-to-background ratio is much worse. Observation of single top quark production has therefore been achieved at the Tevatron only in 2009 [9, 10], after collecting about 100 times more data than available in 1995.

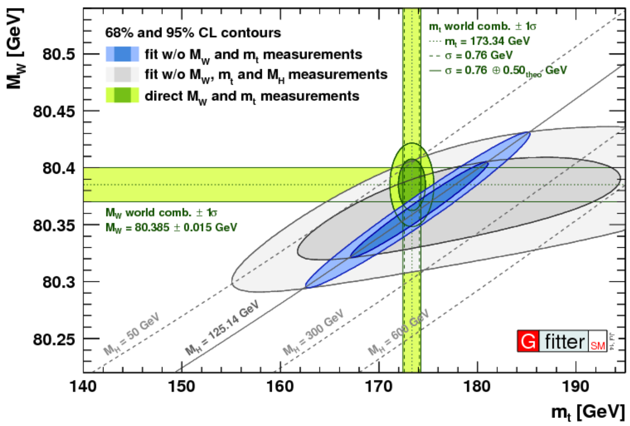

FIG. 5. The Standard Model relates the masses and interaction parameters of the weak bosons with the masses of the top quark and the Higgs boson. Grey lines on the plot indicate predicted Standard Model relations between masses of the top quark, the W boson and the Higgs boson. The narrower blue and larger grey regions are the predicted contours including and excluding the Higgs boson mass measurement, without taking into account measured W boson and top quark masses. The horizontal and vertical bands indicate the 68% confidence level regions of the measured W boson and top quark masses and green contours cover 68% and 95% areas. There is a remarkable agreement between the experimental measurements and the predictions indicating deep self-consistency of the Standard Model.

Since its discovery, all properties of the top quark have been measured at the Tevatron with increasing precision as new data from the 2001-2011 Tevatron run at a center-of-mass energy of 1960 GeV were coming in. Most attention was focused on its mass, which is a crucial property of this particle: it is the only property not predicted by theory and, together with the W boson mass, it constrains the Higgs boson mass (see Fig. 5). The large value of the top quark mass indicates a strong coupling to the Higgs boson, and could provide special insights in our understanding of electroweak symmetry breaking (see Fig. 6). Other properties, including the electric charge, lifetime, spin correlations, and many others, have also been studied by both CDF and D0. Both collaborations have also measured the production cross sections of both $t\bar{t}$ and single top processes, and differential $t\bar{t}$ cross sections as a function of various variables. Scientists have extensively pursued searches for new physics in events with top quarks, including tests of fundamental symmetries in the top quark sector as well as direct searches for new particles coupled to top quarks.

In theoretical calculations, the mass of a particle can be unambiguously related with the experimental value only if the particle is considered in a free state, which is impossible for the strongly interacting quarks. The existing different approximate treatments of the strong interaction effects on the mass lead to an ambiguity in the interpretation of the top quark mass measurements. CDF and D0 have developed many novel measurement techniques in order to both increase the precision of the top quark mass measurement and pin down the ambiguities related with the theoretical interpretation of the measured value. The measurements use $t\bar{t}$ events, because the backgrounds are more manageable in this production mode. The results derived from the various techniques by CDF and D0 are combined to provide the most precise determination of the top quark mass. All techniques rely on the idea that, when top quarks decay, they transfer their kinematic characteristics to the W boson and b quark, and the measured energies and momenta of the final state particles can be used to reconstruct the top quark mass.

However, there are problems that complicate this simple idea and require sophisticated solutions to allow for a precise measurement. The neutrinos produced in top quark decays are not detected and thus their momenta are not measured. They are, instead, inferred from the decay kinematics, by constraining the invariant mass of the charged lepton and neutrino system to the precisely known mass of the W boson. Another difficulty concerns the correct mapping of the experimentally reconstructed objects–jets and charged particle trajectories–to the elementary particles (quarks and leptons) from the decays of the top quark and the W boson. All these ambiguities are accounted for by simulating top pair production and decay, together with the response of the detector to the final state particles, using Monte Carlo methods. The price to pay is the systematic uncertainties introduced by the simulation model, in addition to the uncertainties originating from finite detector resolution. The challenge of the top quark mass measurement, besides the statistical precision which increases as new data come in, is to reduce both types of systematic uncertainties, from detection and from simulation, by developing new ideas and methods. For example, the uncertainty from the relatively low precision measurement of jet energies is reduced by constraining the invariant mass of the jet pair from the W boson decay to the W boson mass–a method known as the *in situ* calibration of the jet energy.

Besides the measurement of the top quark mass, a topic that attracts much attention is the search for resonances in the invariant mass spectrum of top-antitop quark pairs. Such resonances would be a signal of new physics, as they would come from particles heavier than the top quark and thus allowed to decay into $t\bar{t}$ pairs. These

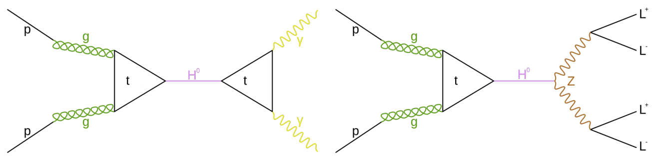

FIG. 6. The top quark plays a central role in the study of electroweak symmetry breaking, providing the most sensitive probe for the Higgs boson production. The Higgs boson couples to mass, so the strongest coupling is to the heaviest particle–the top quark. The strength of this coupling gives rise to the dominant production mode of the Higgs boson by a mechanism known as "gluon fusion", where two gluons from the colliding protons fuse to generate a top quark loop, which then couples to a Higgs boson. The high intensity of incoming gluons in the high energy proton beams at the LHC makes this production mode stronger. The Higgs boson can decay into two massless particles, the photons in the left diagram, again predominantly through a top quark loop, or directly into two massive particles, the Z bosons in the right diagram, which subsequently can decay into leptons (electrons or muons). These two production and decay modes, with their easily identified final states, were the ones used for the discovery of the Higgs boson at the LHC. The observed agreement between the measured and predicted production rates in these modes confirms the strength of the Higgs boson coupling to the top quark and thus supports the electroweak symmetry breaking mechanism described by the Standard Model.

hypothetical particles could interact predominantly with the heaviest quarks either by a modified strong force, such as the massive gluons called "axigluons", or a modified weak force, such as the heavy Z' bosons. Their existence would thus extend the picture of fundamental forces described by the Standard Model. CDF and D0 have set limits that exclude such resonances up to a $t\bar{t}$ invariant mass of about 1000 GeV.

With the higher rates of top pair production due to the higher collision energy of the Large Hadron Collider (LHC) at CERN, which joined the Tevatron in producting top quarks in 2010, and the higher intensity that the accelerator can achieve due to the use of proton beams for collisions, the experiments there are now taking the lead in precision measurements of top quark properties and searches for new phenomena involving top quarks, advancing the methods developed at the Tevatron. Searches in the $t\bar{t}$ invariant mass spectrum at the LHC currently exclude any resonances up to about 2000 GeV. The most recent combination of top quark mass measurements includes results from all Tevatron and LHC experiments and is 173.34 ± 0.76 GeV, which has an accuracy of 0.4%. This is the most precise measurement of mass of any quark, based on the fact that the top quark decays before forming more complex particles.

From all studies, the top quark appears to be a point-like particle; it has no internal structure that we can discern. It has properties very similar to the up and charm quarks, with the exception of its remarkable massiveness and its very short lifetime of 5×10^{-25} seconds. The top quark is about 200 times more massive than the proton, about forty times that of the second heaviest quark (the b), roughly the same as the entire mass of the gold nucleus! Surely this striking obesity holds an important clue about how mass originates.

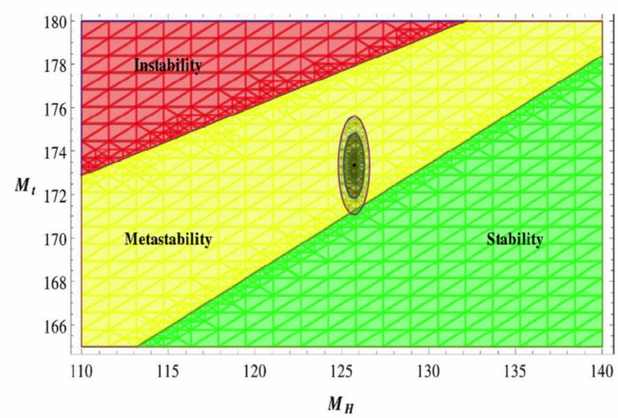

FIG. 7. The Standard Model provides the possibility of predicting from the masses of the Higgs boson and the top quark, whether the present electroweak vacuum state of the Universe is likely to be stable or merely long-lived. A 125 GeV Higgs mass seems to be extremely close to the boundary for stability, but a definitive answer requires much more precise measurements of the top quark mass.

The discovery of the Higgs boson [11, 12] by the ATLAS and CMS collaborations at the LHC is another milestone in particle physics. The hunt for this particle was based for years on constraints of its mass using the top quark and W boson masses as input (see Fig. 5). The Higgs boson measured mass value of 125.15 ± 0.24 GeV, together with the top quark mass and the strength parameter of the strong interaction, turn out to be the key parameters for investigating possible new physics at energies much higher than those currently reachable by accelerators, close to the so-called Planck scale of 10^{19} GeV, where quantum effects start playing a significant role in gravity. New physics in addition to the Standard Model is required to explain the neutrino masses and mixings, as well as dark matter, a species of matter subject to no known interaction other than gravity, for which astronomical data show that it makes the 5/6 of the total matter in the Universe.

It is interesting that the measured Higgs and top masses indicate a particularly intriguing behavior of the Higgs potential. This depends on two terms, one of which determines the Higgs boson mass and the other describes its self-interaction. The latter is varying at short distances, like the electromagnetic and strong interactions, and for some values of the top quark mass it can go negative at very short distances. When that happens, the ordinary minimum in the Higgs potential is not the lowest point and quantum tunneling to a lower-energy state is permitted. This mechanism is described as metastability of the elecroweak vacuum–an unstable state where the Universe can live for a very long, but not infinite, time (see Fig. 7). The Higgs field could have been primordially trapped there, leading to a stage of inflation, which is another subtlety of the Universe that astronomical data indicate: a sudden expansion of space at some early time in its evolution. Since the dependence of this effect on the top quark mass is strong and quite subtle, it is not surprising that different groups of theoretical physicists slightly disagree in the interpretation of the results, some of them favoring and others disfavoring vacuum metastability. An electron-positron collider capable of producing top quarks is needed to provide a more precise top quark mass measurement, limited at hadron colliders by systematic uncertainties. Such a collider, currently under active consideration, could be able to discriminate between vacuum stability and metastability.

The top quark discovery and exploration of its properties are the flagship Tevatron legacy. After nearly 30 years from the foundation of the Standard Model, this discovery completed the roster of fundamental constituents of matter in the Standard Model. The Tevatron experiments, CDF and D0, studied extensively the properties and interactions of the top quark with the other fields of the Standard Model. Many searches in the top quark sector have been performed at the Tevatron, testing fundamental symmetries of the Standard Model and setting sensitive exclusion limits on many new physics scenarios. The precision of measurements reached at the Tevatron has been driving the advance of theoretical top quark physics calculations over many years. Further studies of the heaviest known elementary particle at the LHC and the planned electron-positron collider could shade light on physics phenomena beyond what we know today.

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