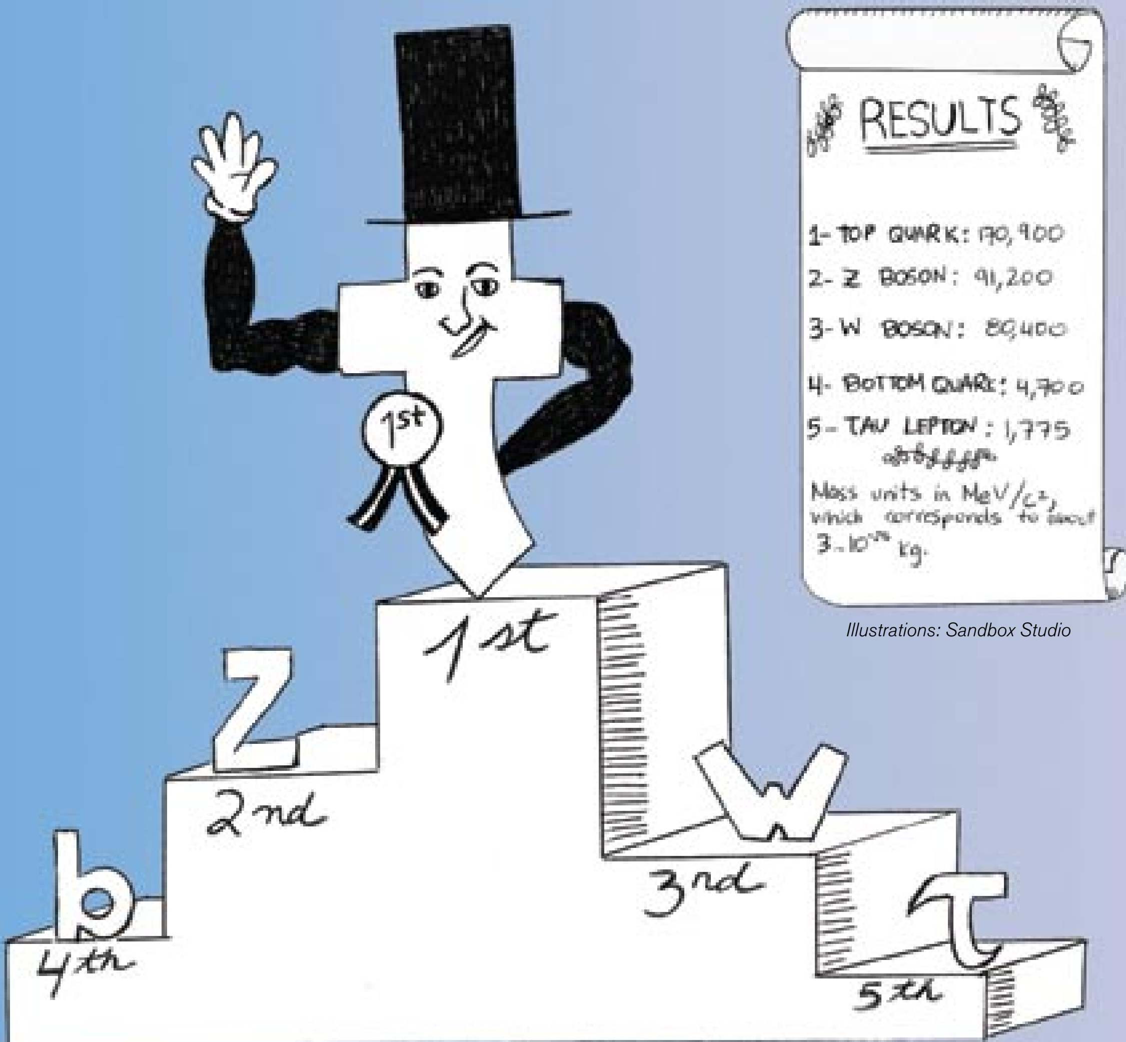
Secrets of a HEAVYWEIGHT

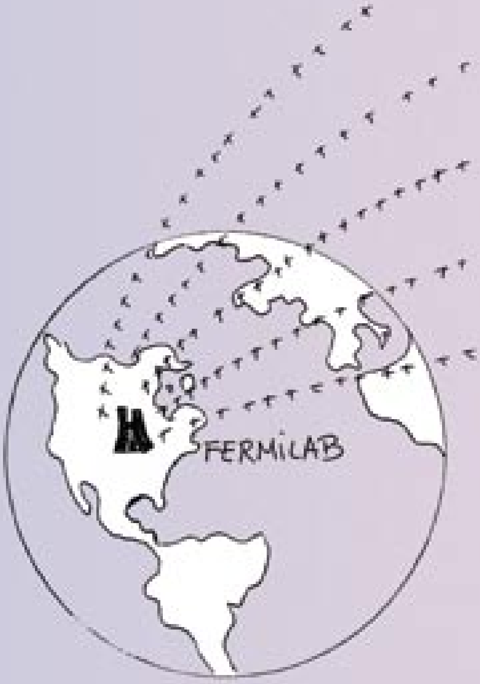


Illustrations: Sandbox Studio

A dozen years after it first appeared on the world stage, the top quark is still one of the hottest topics in particle physics. Why is it so much heavier than any other particle? And what can it tell us about the origin of mass and other quantum mysteries? Here's a look at the top's quirky nature, its fevered past and its promising future.

by Kurt Riesselmann

THE RAREST OF BEASTS

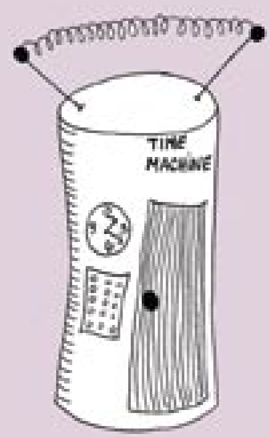


The top quark is the rarest and heaviest fundamental particle ever sighted. All the top quarks observed on Earth come from a single place—the Tevatron collider at Fermi National Accelerator Laboratory, the only machine powerful enough to create them. At first, in the 1990s, only a few dozen were produced per year; today the collider cranks out thousands annually, and 1300 scientists from all over the world eagerly pounce on every trace these freshly minted tops leave behind.

"We now have enough top quarks in our data that we can measure things that physicists could only dream of" in those early days, says Kevin Lannon of Ohio State University. But extracting information from those quarks is not easy, he adds: "We certainly don't have them all sitting in a bucket under a microscope; otherwise we would know more."

TIME MACHINE

While it's hard to make top quarks in the laboratory, theorists think they were abundant in the early universe. The big bang released an enormous amount of energy that allowed for the creation of extremely heavy particles—many even heavier than the top quark. So producing top quarks in a laboratory is like climbing into a time machine. It also raises intriguing possibilities: Will colliders eventually spit out particles even heavier than the top? And will some of those super-heavyweights decay into things that have never been seen before?



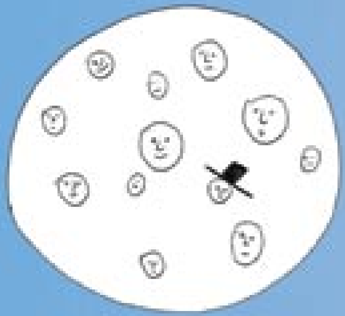
THE HIGGS CONNECTION

What can you do with a top quark? For one thing, you can learn more about the famous Higgs particle, which gives all the other elementary particles their mass. No one has managed to observe the Higgs. But measuring the mass of the top offers a roundabout way to home in on the Higgs' mass, since their masses are mathematically linked. That's why scientists working on two Fermilab experiments, CDF and DZero, are eager to measure the mass of the top quark with ever greater precision; their latest combined result has an uncertainty of about one percent.

In fact, the top is so heavy—about 40 times more massive than its cousin, the bottom quark—that some people wonder whether it also plays a role in giving other particles their mass, another intriguing question to explore.

HEAVY, YET SUPER-SLIM

Even though top quarks are the heavyweights of the subatomic world, that doesn't mean they're a size XXL. As is the case for all elementary particles, quantum theory forces the top quark into a mathematical corset with no spatial extent. This means they are point-like, with zero diameter, and take up no space at all. Curiously, though, when quarks combine to form protons and other particles, those composite particles do take up space. Experimentalists, of course, take nothing for granted, and continue to probe the top quark's fundamental properties. Could it, like the proton, contain even tinier particles? If so, it would not be considered point-like anymore.

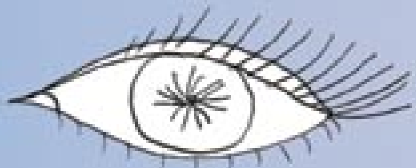


THE TOP MAKES YOU HEAVIER, TOO

Every minute of every day, the top quark affects the world around us and every atom in our bodies. In particular, top quarks have a virtual presence inside every proton and neutron. The uncertainty principle of quantum mechanics allows top quarks to quickly wink in and out of an ephemeral presence. These virtual processes contribute to the proton's mass—and the mass of every human being.

BLINK AND YOU'LL MISS IT

The top quark decays much, much faster—a million billion billion times faster—than you can blink. Of the six quarks known to exist in nature, the top is by far the most short-lived. Theorists estimate that each top quark, after it pops into existence, decays into two lighter particles in less than 10^{-24} seconds.

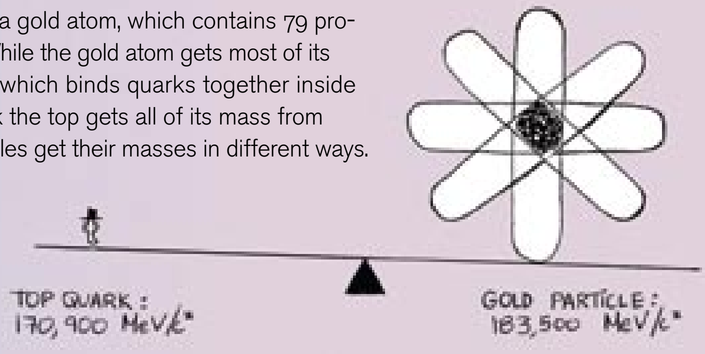


NO TIME TO MARRY

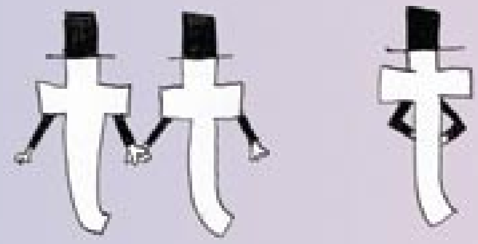
Quarks hate being alone. As soon as a quark emerges from a particle collision, it grabs another quark or two to form pairs and threesomes. This phenomenon is known as quark confinement. The top quark, however, is so short-lived it doesn't have time to find and bond with a mate. Instead, it quickly decays into two particles, a *W* boson and a bottom quark. For scientists, this is a golden opportunity to learn about the fundamental properties of quark decay without having to take those messy quark pairings into account.

WORTH ITS WEIGHT IN GOLD

One top quark is almost as heavy as a gold atom, which contains 79 protons, 118 neutrons, and 79 electrons. While the gold atom gets most of its mass from the strong nuclear force, which binds quarks together inside protons and neutrons, physicists think the top gets all of its mass from the Higgs particle. So, curiously, particles get their masses in different ways.



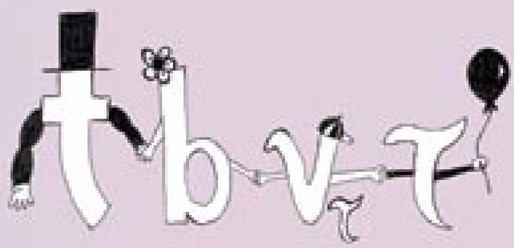
ONE AT A TIME



Beyond giving clues about the Higgs particle, the continuing dissection of the top quark is uncovering new facets of the subatomic world. In late 2006, the DZero collaboration reported evidence for a new quantum process that produces top quarks one at a time, rather than in the usual pairs. Looking for this rare process has taught experimentalists many new tricks and techniques that they can now apply to other particle searches. As the Tevatron continues to crank out more top quarks, scientists are optimistic that they will make more such discoveries. The discovery of single-top production by both Tevatron experiments would bring scientists one step closer to finding the Higgs.

A FOURTH FAMILY?

The fundamental building blocks of matter—quarks and leptons—naturally fall into three particle "families," each containing two quarks and two leptons. Could there be a fourth family, or even more exotic particles? If so, they could be even heavier than the top, not to mention harder to produce. But the Tevatron collider might have a chance. The CDF and DZero experiments are looking for evidence for new quarks and other particles by carefully studying the production and decay of top quarks. The current model of particle interactions predicts that every top quark decays into a *W* boson and a bottom quark. If experimenters find out otherwise, it means new particles are lurking just around the corner.



EINSTEIN'S RECIPE

Albert Einstein never heard of the top quark. Yet his famous equation, $E=mc^2$, is the key to understanding how much energy it takes to make a top quark. The collision of two particles with sufficiently high energy, E, can create a top quark with mass m. But what is sufficient? Not knowing how massive the top quark was, scientists initially tried to create it with accelerators that were not powerful enough to do the job.

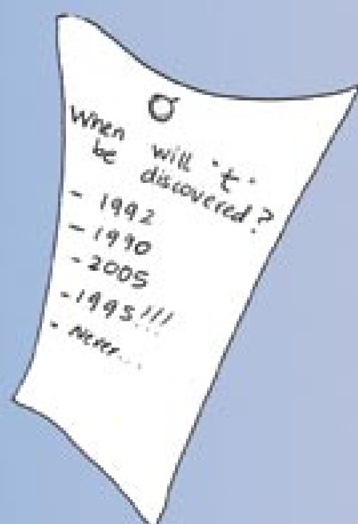
FALSE ALARM

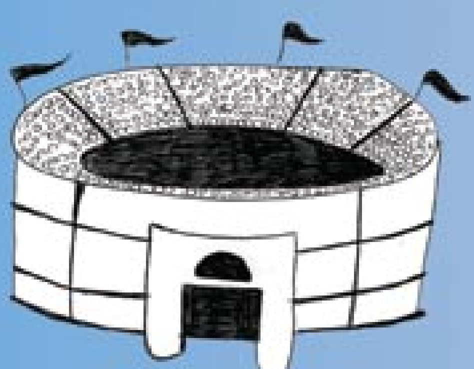
In 1984, scientists at CERN, the European particle physics lab in Switzerland, thought they had caught a glimpse of the top quark. The UA1 collaboration claimed it saw evidence for particle collisions that were best explained by the production of single top quarks. But their findings could not be confirmed.

Terry Wyatt, now at the University of Manchester, joined the UA1 experiment shortly after that announcement. "I was asked to co-convene the group in UA1 that was supposed to confirm this discovery in a larger dataset," he says. "Unfortunately, we found that not only could we not re-discover single top in the new dataset, we could not even re-discover it in the already published dataset. This 'failure' did not endear me to my boss at the time."

TOP BETS

As more and more particle accelerators came up short in their efforts to produce the elusive top quark, it became clear that the top was much heavier than anticipated and would require much more energetic collisions to force it out into the open. A group of physicists at the University of Wisconsin–Madison began to ask fellow scientists to write down their guesses for how heavy the top quark would be and when it would be discovered; the list of predictions was posted in their office. "I think we put it up in 1989, and it was added to as time went on," says theorist Tom Rizzo, now at the Stanford Linear Accelerator Center, who won the game when the particle was discovered in 1995. But pride was his only reward; Rizzo does not recall collecting a prize for his winning bet.



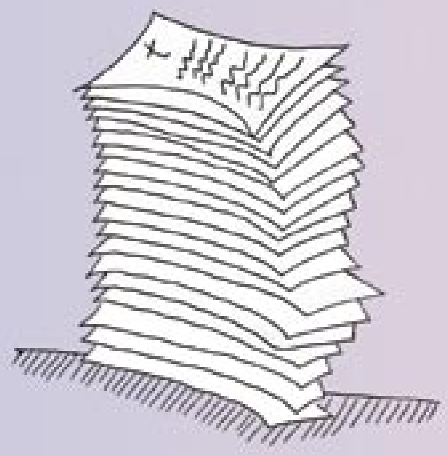


WHERE'S WALDO?

The signals left by different subatomic processes can look very similar. So looking for a top quark signal in a pile of particle data is like spotting a particular person in a sold-out football stadium, knowing that impersonators are in the crowd as well. Particle physicists rarely announce a discovery based on a single sighting of a quark or any other particle; instead, they keep looking for more candidates. This helps avoid cases of mistaken identity.

A PHOTO FINISH

In 1993, when the DZero experiment recorded an extraordinary particle collision that stood out from anything seen before, a debate ensued. Scientists agreed that the pattern could stem from the decay of a top quark, but some cautioned that it could also be due to an entirely new form of interaction. More data were needed. Just across the Tevatron collider ring, physicists of the CDF experiment were feverishly looking for signs of the top as well. Short of claiming a discovery, they reported first evidence for the top quark in 1994. By early 1995, both experiments had gathered enough data. Like sports teams finishing in a tie, CDF and DZero called a joint press conference and officially declared the discovery of the top quark on March 2, 1995, bringing the 18-year search to an end. But for scientists, the discovery marked a new beginning: There were many more things to find out about the mysterious particle.



HOT TOPIC

Since 1977, when the search for it began, the top quark has been the subject of more than 8000 scientific papers. The particle physics community still publishes about 300 papers a year related to the top—an indication of continued interest in the particle. More than 250 graduate students have received PhDs for related research.

COMING SOON: A TOP QUARK FACTORY

The Large Hadron Collider (LHC), scheduled to start operations at CERN next spring, will produce particle collisions with seven times as much energy as the Tevatron collider. "The LHC will be an efficient top quark factory," says theorist Bogdan Dobrescu of Fermilab. While the Tevatron produces thousands of top quarks per year, the LHC is expected to crank out millions. By examining this deluge of top quarks in detail, scientists hope to learn why the top quark is so heavy and how its properties are tied to the breaking of one of the fundamental symmetries of particle theory, thereby giving some mass to elementary particles.