Top-ophilia*

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January 11, 2008

1 Room for the Top

Almost from the moment in June 1977 when the discovery of the Upsilon resonance revealed the existence of what we now call the bottom quark, physicists began searching for its partner. Through the years, as we established the electric charge and weak isospin of the b-quark, and detected the virtual influence of its mate, it became clear that the top quark must exist. Exactly at what mass, we couldn't say, but we knew just how top events would look. We also knew that top events would be rare—if the Tevatron could make them at all—and that picking out the events would pose a real challenge for the experimenters and their detectors.

2 On the Trail to Top

Fermilab celebrated the eightieth birthday of our Founding Director, Bob Wilson, on March 4, 1994. Recounting how physics had changed since Wilson's youth, I spoke of my excitement about the search for top and my admiration for human beings who were doing the nearly impossible [1].

> Just over a year ago, in this auditorium, the CDF Collaboration showed an event—a computer reconstruction—that could represent the production and decay of a top quark and a top antiquark. The unmistakable signature of top-antitop production, as all of us had been saying for years, would be a top decaying into bottom + electron + unobserved neutrino, together with an antitop decaying into antibottom + muon + unobserved neutrino. We look for one electronic decay and one muonic decay because that combination occurs rarely in ordinary topless events. The top and antitop both decay essentially at the instant they are produced. Each bottom quark travels a few millimeters or so before decaying into a charmed quark and other particles. The chain of events that would signal top is easy to sketch on a blackboard, but requires extraordinary efforts to record and decode.
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> In addition to the usual blizzard of particles, the CDF event has a muon and an electron, both far from other tracks, so relatively easy to identify, plus a few tracks that originate not from the point where proton and antiproton collided, but from a point 3 millimeters away—just as a bottom-decay would. The silicon vertex detector can resolve a secondary decay about a tenth of a millimeter from the collision point.
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> The machine that gave us this picture is about three stories high, weighs 5000 tons, contains 100,000 channels of electronics, and has, buried deep within it, that fantastically precise silicon vertex detector. What an enormous step this is from the primitive detectors of Bob Wilson's youth! The only thing that hasn't changed is how experimenters spend their time. In the good old days, experimenters sat in darkened rooms, staring straight ahead, waiting for charged particles to make bright spots on phosphor-coated screens. Today, experimenters sit for hours watching charged particles make bright spots on the phosphor-coated screens of their computer displays.
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> This picture (Figure 1) was extremely significant to me. I remember having a powerful emotional reaction. It really didn't matter at the time whether this particular event was a top and antitop, it was just so amazing that people had made a device that could see, in real space and under the battle conditions of an experiment, all the elements of the top-antitop signature. Learning how the detector really behaves and what nasty surprises Nature has up her sleeve is what sepa-

*Reminiscence for the *Top Turns Ten* Symposium at Fermilab, October 21, 2005 `http://www.fnal.gov/pub/news05/TopTurnsTen.html`.

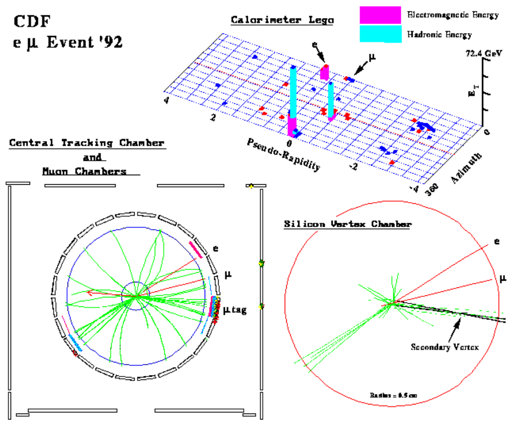

Figure 1: Something

Top Quark, Last Piece in Puzzle Of Matter, Appears to Be in Place

By WILLIAM J. BROAD (NYT) 1809 words
Published: April 26, 1994

The quest begun by philosophers in ancient Greece to understand the nature of matter may have ended in Batavia, Ill., with the discovery of evidence for the top quark, the last of 12 subatomic building blocks now believed to constitute all of the material world.

An international team of 439 scientists working at the Fermi National Accelerator Laboratory will announce the finding today, bringing nearly two decades of searching to a dramatic conclusion.

The Fermilab discovery, if confirmed, would be a major milestone for modern physics because it would complete the experimental proof of the grand theoretical edifice known as the Standard Model, which defines the modern understanding of the atom and its structure. The finding is likely to produce waves of intellectual satisfaction for physicists around the world and to give American physics a significant boost.

Figure 2: Opening paragraphs of the *Times* front-page story on CDF's "evidence" paper [2].

rates the experimental sheep from the goats—and I guess they are still separating—but this picture showed me that the possibility of discovering top had become real. I was moved by the improbability of that feat. It's really a wonderful achievement, even if we don't yet know the answer.

3 The End of Particle Physics?

I was in Santa Barbara in late April when CDF presented its "evidence" paper, but could read all the information thanks to what I believe was the first use of the World Wide Web to document an announcement in particle physics.

The New York *Times* account (Figure 2) was a little extravagant, but I thought it was fun and harmless—until UCSB experimentalist Jeff Richman phoned. "My graduate students have read the *Times* article," he said, "and they think particle physics is over! You have to do something!" I did what any red-blooded theorist would do; I agreed to give a seminar. Then I began to worry: if I just told the students what they already should have known about the top quark, I would confirm their mistaken impression that particle physics was over. I had to think of something new—fast! My desperation led me to work out the influence of top on the strong coupling constant we measure at low energies (Figure 3), and to realize that top influences the proton's mass: $M_p \propto m_t^{2/27}$.

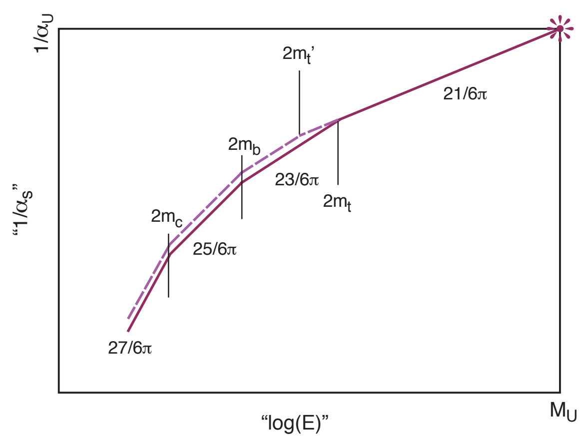

Figure 3: Two evolutions of the strong coupling constant α_s. A smaller value of the top-quark mass leads to a smaller value of α_s.

4 Top is Found!

It wasn't long until CDF and DØ presented the definitive evidence for top that we celebrate in *Top Turns Ten.* With the discovery came much attention to the implications of heavy top. In a public lecture at the Aspen Center for Physics in the summer of 1995, I sought (Figure 4) to dispel the notion that the top quark was remote and insignificant for the world around us.

It is popular to say that top quarks were produced in great numbers in the fiery cauldron of the Big Bang, disintegrated in the merest fraction of a second, and vanished from the scene until my colleagues learned to create them in the Tevatron, a giant particle accelerator near Chicago. That would be reason enough to care about top: to learn how it helped sow the seeds for the primordial universe that evolved into our world of diversity and change. But it is not the whole story; it invests the top quark with a remoteness that veils its real importance—and it denies the immediacy of particle physics.

The real wonder is that here and now, every minute of every day, the top quark affects the world around us. Through the uncertainty principle of quantum mechanics, top quarks and antiquarks wink in and out of an ephemeral presence in our world. Though they appear virtually, fleetingly, on borrowed time, top quarks have real effects.

A few numbers regulate the dimensions and character of the everyday world, from the size of atoms to the energy output of the sun. Only a generation ago, these parameters of the quotidian—the mass of the proton, the mass of the electron, and the strengths of a few fundamental forces—seemed givens, beyond the compass of science. Today, we have begun to discern links among them, to see how each of them might be understood and, eventually, computed.

The proton, the basic unit of the atomic nucleus of all the elements, is itself composed of up quarks and down quarks. We have discovered that the proton's mass is due mostly to the energy stored up in the "strong" force that holds the quarks together. By studying the force between quarks, we learn why the proton is the way it is.

We now believe that all the subatomic forces have equal strengths at very high energies. We perceive distinct strong, weak, and electromagnetic interactions because the symmetry—the perfection—that is evident at high temperatures is hidden in our low-energy world. Everything that happens from very high temperatures down to low temperatures is encoded in the way the forces evolve from the state of perfection to the state of nature.

Since top stands apart as very much heavier than the others, it has a special influence on the evolution of the strong force, and so on the mass of the proton. If top weighed a bit more or less, the force that confines quarks inside a proton would be slightly stronger or weaker. The resulting change in the proton's mass would give our world a different character. The top quark's mass is expressed in the form of every flower and grain of sand, in every human face.

TOP MATTERS!

THIS BROADSIDE WAS PRODUCED ON THE OCCASION OF CHRIS QUIGG'S TALK, "TOP QUARK SECRETS: POSTCARDS FROM THE PARTICLE FRONTIER," IN THE HEINZ R. PAGELS MEMORIAL LECTURES ORGANIZED BY THE ASPEN CENTER FOR PHYSICS, AUGUST 2, 1995.

Figure 4: "Top Matters" broadside for the Aspen Center for Physics, 1995.

In 1997, "*Top*-ology" appeared as a *Physics Today* cover story [3]:

> Top is a most remarkable particle, even for a quark. A single top quark weighs 175 GeV, about as much as an atom of gold. But unlike the gold atom, which can be disassembled into 79 protons, 79 electrons, and 118 neutrons, top seems indivisible, for we discern no structure at a resolution approaching 10^{-18} m. Top's expected lifetime of about 0.4 yoctosecond (0.4×10^{-24} s) makes it by far the most ephemeral of the quarks. The compensation for this exceedingly brief life is a measure of freedom: top decays before it experiences the confining influence of the strong interaction. In spite of its fleeting existence, the top quark helps shape the character of the everyday world.

"*Top*-ology" introduced the iconic time series that compares indirect determinations of the top mass with measurements. It also rekindled the friendly DØ–CDF competitive spirit when *Physics Today*'s art director chose the "wrong detector" (in half of the world's opinion) for the cover. I made a second version for the injured parties to send to their mothers! You may make your own assignment of authentic and counterfeit in Figure 6.

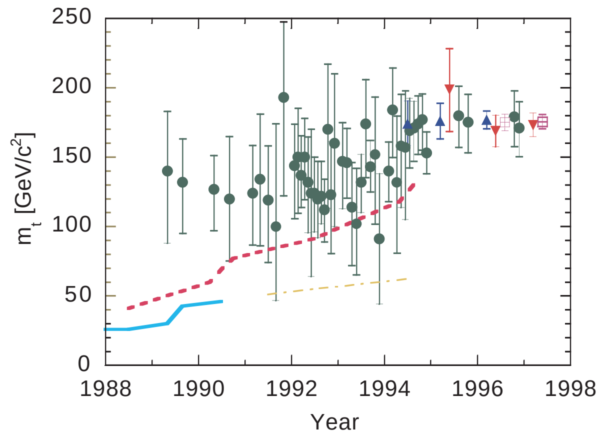

Figure 5: Indirect determinations of the top-quark mass from fits to electroweak observables (open circles) and 95% confidence-level lower bounds on the top-quark mass inferred from direct searches in e^+e^- annihilations (solid line) and in $\bar{p}p$ collisions, assuming that standard decay modes dominate (broken line). An indirect lower bound, derived from the W-boson width inferred from $\bar{p}p \to (W \text{ or } Z) +$ anything, is shown as the dot-dashed line. Direct measurements of m_t by the CDF (triangles) and DØ (inverted triangles) Collaborations are shown at the time of initial evidence, discovery claim, and 1997. The 1997 world average from direct observations is shown as the crossed box.

References

[1] Chris Quigg, "A Little Bit of the Gods," Presented at the International Symposium and Tribute in Honor of Robert R. Wilson on His 80th Birthday *Celebrating an Era of Courage and Creativity*, Fermi National Accelerator Laboratory, March 4, 1994, under the title, "Golden Ages." Available at `http://lutece.fnal.gov/Notes/SplashGods.pdf`

[2] William J. Broad, "Top Quark, Last Piece in Puzzle Of Matter, Appears to Be in Place," New York *Times* front page, April 26, 1994.

[3] Chris Quigg, "*Top*-ology," *Phys. Today* **50**, 20 (May, 1997); extended version circulated as `http://arXiv.org/abs/hep-ph/9704332`.

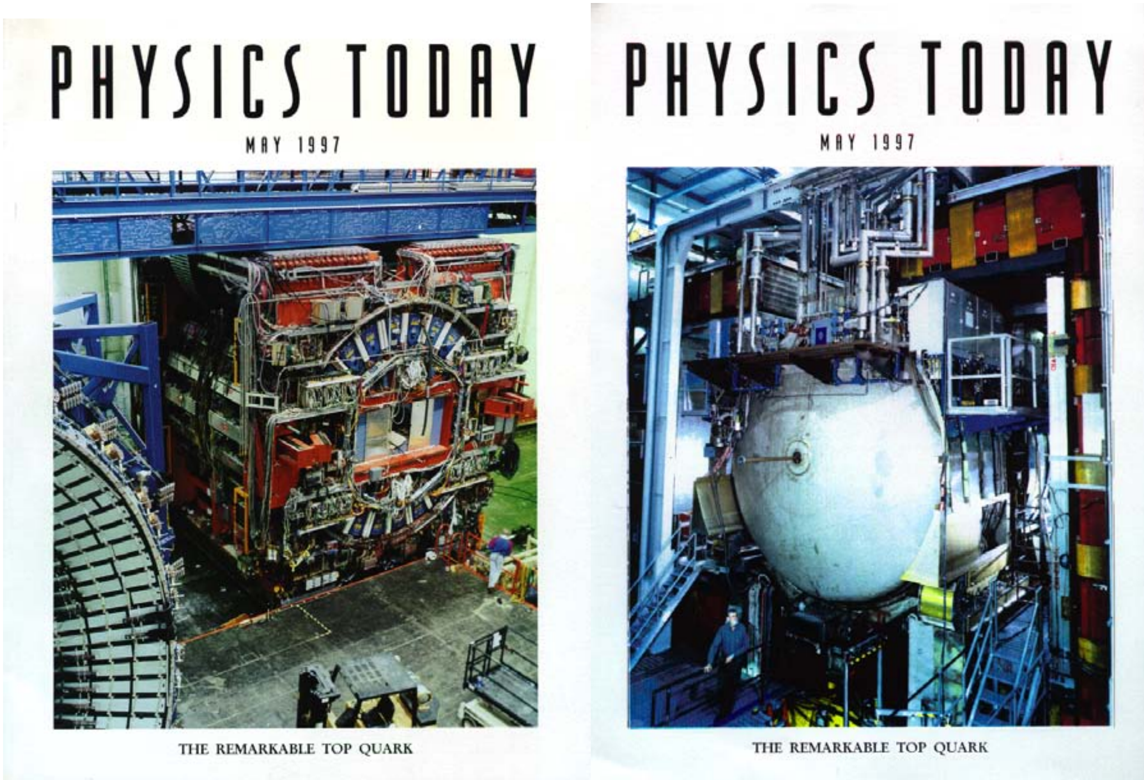

Figure 6: Which is the impostor?