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Top Quark

Completing the Third Generation

No one could doubt that there would be a sixth quark, the top or t, but it was equally certain that initially no one knew where it would be found. With the b quark near 5 GeV, 15 GeV or so seemed reasonable for the mass of the top quark. Every new accelerator that came on line had the potential to make the discovery and every one of them came up empty handed. Particularly disappointing were the cases of TRISTAN, an e^+e^- collider at KEK, which reached c.m. energy of 61.4 GeV and set a lower bound of 30.2 GeV and the Sp$\overline{\text{p}}$S collider at CERN, which found the W and Z. Even SLC and LEP searched to no avail, setting limits at half the mass of the Z. This left the search to hadron colliders.

In 1984 and 1985 CERN's S$p\overline{p}$S collider reigned as the world's highest energy machine, with $\sqrt{s} = 630$ GeV. Having already discovered the W and Z, it was positioned to look for the top quark through the decay $W \to t\overline{b}$ and early results from UA-1 gave evidence for a top-quark with a mass of 40 ± 10 GeV. However, additional running and further analysis did not confirm the result but instead produced a bound of 55 GeV.

With further running at the S$p\overline{p}$S in 1988-9 both UA-1 and UA-2 improved this limit. Using signals from muons and jets, UA-1 ruled out a top quark below 60 GeV, while UA-2, which looked in the electron plus jets channel excluded masses below 69 GeV.

The original accelerator at Fermilab began operation in 1972 with an energy of 200 GeV. At the time of the discovery of the Υ in 1977, it was operating at 400 GeV. Fermilab pioneered the use of superconducting magnets, which increased the operating field to 4 T, allowing the beam energy to be doubled to 800 GeV. Following the lead of the SPS at CERN, Fermilab also constructed a ring in which antiprotons could be accumulated. The Tevatron Collider brought together protons and antiprotons inside the main ring. Through this series of improvements, the operating c.m. energy of the machine increased from about $\sqrt{s} = 20$ GeV to $\sqrt{s} = 1.6$ TeV, from which it was subsequently raised to 1.8 TeV.

The first detector at the Tevatron Collider was CDF, the Collider Detector Facility. A descendant of UA1 and UA2, CDF featured cylindrical geometry, tracking with a drift chamber inside an axial magnetic field of 1.4 T, and both electromagnetic and hadronic calorimetry outside the magnet. The final layer provided for muon detection and measurement. During the 1988-89 run, a total of 4 pb^{-1} was accumulated. With these data, CDF made an improved determination of the Z mass $90.9 \pm 0.03 \pm 0.02$ GeV, the W mass 79.9 ± 0.39 GeV, and studied B meson production. At the same time, the lower limit on the top quark mass was raised to 77 GeV. Adding additional channels moved the limit higher, to 85 GeV, then to 91 GeV.

A second detector at the Tevatron Collider, D0, was completed in 1992. It complemented CDF by optimizing calorimetry at the cost of tracking. In particular, it had no magnetic field in its tracking region. D0's advantage lay in measuring jets at high transverse momentum and in detecting missing transverse momentum, a sign of neutrinos or other non-interacting particles. The energies of electrons and muons could be measured using electromagnetic calorimetry for the former and magnetized absorbers in the outermost layers for the latter.

The Standard Model gave no direct information on the mass of the top quark, for all the quark masses are simply arbitrary parameters. However, using detailed electroweak measurements it was possible to make inferences about the mass of the top quark. Of all the particles in the Standard Model, only the t and the Higgs remained to be discovered. The prediction of the W mass in terms of the Z mass in lowest order is

$$M_W^2 = \frac{1}{2} M_Z^2 \left(1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F M_Z^2}} \right). \tag{14.4}$$

The W and Z can undergo virtual transitions, the W to $t\bar{b}$ and the Z to $t\bar{t}$ or $b\bar{b}$. These result in small radiative corrections to the relation between their masses. It is also possible for the W and Z to make virtual transitions by emitting and reabsorbing a Higgs particle. It turns out that the mass of the Higgs boson enters these effects only as $\ln m_H^2$ while there are corrections to the W and Z masses squared proportional to m_t^2, as discussed in Chapter 13. A good measurement of the W mass together with a rough guess for the Higgs mass was enough to make a reasonable prediction of the mass of the top quark. By 1994, these estimates centered on values around 180 GeV.

Though the mass of the top was uncertain, its behavior was completely predicted by the Standard Model. Once the limits on the top mass exceeded the mass the W it was clear that its decay would be $t \to W^+ b$, whose width is

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_Z^2} \right)^2 \left(1 + 2\frac{m_W^2}{m_Z^2} \right). \tag{14.5}$$

If the t quark were well above the bW threshold, this width would be on the order of a GeV, meaning that any narrow bound states $t\overline{t}$ would be complete obscured. More picturesquely, the t would decay before it could bind.

The W^+ could decay leptonically to $e^+\nu_e$, $\mu^+\nu_\mu$, or $\tau^+\nu_\tau$, or nonleptonically, primarily to $u\overline{d}$ or $c\overline{s}$. Since the t was pair produced, there were four general forms for the events:

$$\begin{array}{llcll} t\to & b(\ell^+\nu) & \overline{t} & \to & \overline{b}(\ell^-\overline{\nu}) \\ t\to & b(q\overline{q}) & \overline{t} & \to & \overline{b}(\ell^-\overline{\nu}) \\ t\to & b(\ell^+\nu) & \overline{t} & \to & \overline{b}(q\overline{q}) \\ t\to & b(q\overline{q}) & \overline{t} & \to & \overline{b}(q\overline{q}) \end{array} \tag{14.6}$$

The last of these would be particularly hard to isolate since these events would be masked by much more common events in which jets were produced by ordinary QCD interactions. Leptons were thus the key signature for the t quark. The b and q and $\overline{q}$ quarks would appear as jets while the neutrinos would result in large missing "transverse energy," i.e. a transverse momentum imbalance.

The Tevatron Collider resumed running in 1992 and collected data during Run Ia (1992-3) and Run Ib (1994-5). Using Run Ia data, D0 raised the limit on the top quark mass to 131 GeV. By May 1994, CDF had enough events to declare that they had "evidence for the top quark," though they stopped short of announcing its discovery. Two events were found that contained both an e and a μ, and which had both two additional jets (presumably from the bs) and missing transverse energy. Events in which a single lepton was found faced more severe backgrounds and additional requirements had to be imposed. Only events in which there were three or more jets were considered. In addition, there had to be evidence that at least one jet came from a b. This evidence was obtained in two ways. A lepton too "soft" (i.e. with not very high transverse momentum) to indicate a W was circumstantial evidence for the semileptonic decay of a b. Alternatively, the presence of the b could be demonstrated by finding a sign of the B decay itself.

The silicon vertex detector (SVX), the innermost part of CDF's tracking system, could measure tracks with a precision of tens of microns. This was good enough to identify B decays, for which a typical decay length would be $c\tau = 450\ \mu$m times the boost due to the motion of the B. In this way, six events were found, with a background of 2.3 ± 0.3. The soft lepton tag found seven with a background of 3.1 ± 0.3. Three of the seven had SVX tags as well.

The mass of the t quark could be obtained from the events with a single lepton (and thus just one missing neutrino). Seven of the ten events had four or more jets and those with the highest transverse momentum were used to fit the hypothesis $(b\ell\nu)(bq\overline{q})$ where the bs and qs would appear as jets. This kinematical fit gave a mass determination (though no discovery was claimed!) of $m_t = 174\pm10^{+10}_{-12}$ GeV.

In February, 1995, both CDF and D0 were ready to declare the top quark found. CDF had 48 pb^{-1} of new data to add to their previous 19 pb^{-1}. Moreover, improvements in the silicon vertex detector increased its efficiency for finding b

vertices in top events by a factor of two, to about 40%. There were 21 events in the data sample in which the SVX found vertices that were candidates for b decays. In six of the events, two jets were tagged. Additional candidates with soft lepton tags together with jets were identified. Six dilepton events were recorded. The refined mass measurement, $m_t = 176 \pm 8 \pm 10$ GeV, was quite close to that in the earlier CDF paper.

The D0 Collaboration had to overcome handicaps in the design of their detector, which was less suited for the task than was CDF, lacking both a magnetic field and a high precision silicon tracking device. The basic strategy was the same as for CDF: identify leptons as candidates for decays of Ws and jets as candidates for both the b quark-jets and products of nonleptonic W decays. To compensate for the limitations of the detector, D0 developed effective cuts that reduced background, in particular a cut on the total transverse energy. In the dilepton channels, two jets were required as well as missing transverse energy. In the single lepton channels, at least three jets were required. This was increased to four for events in which there was no lepton tag that would signal a b quark. Combining seven channels, D0 found 17 events with an anticipated background of 3.8. With their sample, D0 was not able to determine the mass with as much precision as CDF. Their result, $m_t = 199\ ^{+19}_{-21}$ GeV, was consistent, however, with the CDF result.

Subsequent running at the Tevatron Collider enabled both experiments to observe additional top quark events and to reduce the uncertainty in the mass measurement. Their measurements in both dilepton and single lepton channels were in good agreement. By 1998, the combined result $m_t = 173.8 \pm 5.2$ GeV had the smallest fractional error of any quark mass determination.

The $t\bar{t}$ pairs are produced in two ways: $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$. Calculations show that at the Tevatron Collider, the former dominates. It is also possible to produce a single top quark through processes like $u\bar{d} \to W^+ \to t\bar{b}$, but these should not have passed the cuts imposed by the CDF and D0 experiments. The predicted cross section for $t\bar{t}$ is about 5 pb at the Tevatron Collider. The cross sections measured by CDF and D0 are near this, $7.6^{+1.8}_{-1.5}$ pb and 5.5 ± 1.8 pb.

While the general agreement between the expected and measured cross sections and the conformity of the event structure to that anticipated from the Standard Model provides evidence that we do understand these processes, more exacting tests are needed to exclude exotic alternatives. The top quarks might, for example, be decay products of more massive particles rather than directly produced themselves. Absent such a surprise, the t may seem the most mundane of all quarks. Because of its rapid decay it doesn't produce stable hadrons as do all other quarks. In the t the quark concept is reduced to its most fundamental. Its interactions are for the most part described by perturbative QCD.

But this may be an illusion. Does the very large mass of the t quark point to a special role? Is it an indication of some new interactions not enjoyed by the lighter quarks?

EXERCISES

14.1 A t quark decays into a b quark, whose momentum is measured, and W, which decays to $\mu\nu$. The momentum of the μ is measured and the momentum of the ν transverse to the beam direction, p_ν, is inferred from the missing transverse momentum in the event. If the transverse and longitudinal components of the muon momentum are $p_{\mu\perp}$ and $p_{\mu||}$, find the two possible values of the longitudinal momentum of the ν. When is there no solution for the longitudinal momentum of the ν?

14.2 The coupling of the t, b, and W is described by

$$\frac{g}{\sqrt{2}}\overline{b}_L\gamma\cdot Wt$$

where $b_L=\frac{1}{2}(1-\gamma_5)b$. Here b and t stand for the corresponding spinor fields and W for its field. The square of the decay matrix element can be shown (perhaps by the reader) to be

$$\frac{g^2}{2}[2p_b\cdot\epsilon p_t\cdot\epsilon-p_b\cdot p_t\epsilon\cdot\epsilon]$$

The polarization of the W is ϵ, which obeys

$$\epsilon\cdot\epsilon=-1;\epsilon\cdot p_W=0$$

The three polarizations of the W are given by two choices of three-vectors perpendicular to the momentum of the W (transverse polarization) and one choice with both a time component and a space component parallel to the momentum of the W. (In writing the square of the matrix element the polarization vector was assumed real so the tranverse polarizations must be linear.) Using the two-body decay formula

$$d\Gamma=\frac{1}{32\pi^2}|\mathcal{M}|^2\frac{p_{cm}}{M^2}d\Omega$$

confirm the formula in the text for the decay rate of the t. Show that the ratio of longitudinal to transverse W's is $\frac{1}{2}(m_t^2/m_W^2)$.

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