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Electroweak Reconciliation

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ABSTRACT

New measurements of the mass of the top quark and the production and decay of the heavy boson Z^0 bring the structure of the weak interactions into satisfying focus.

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High-energy physicists view themselves as intrepid explorers, searching for new concepts of space and time. So it is sometime difficult for them to accept that the theories in their textbooks actually work well. Over the past few years, however, experiments have tested the elementary couplings of the weak interaction—the basic force that gives rise to radioactive decay—and, with remarkable precision, the results have converged on the standard textbook model. The experiments confirm the elementary couplings of this interaction to the basic constituents of matter, the leptons (such as the electron) and the quarks (from which the proton and other nuclear particles are made). The observed large mass of the heaviest quark, the top quark, plays a key role in this reconciliation. The results close a chapter in the history of particle physics and present some interesting clues to the content of the next chapter.

The heavy particles $W^\pm$ and Z^0 which mediate the weak interactions were discovered in 1982 in proton-antiproton annihilation experiments at CERN [1, 2]. The masses of these particles are 80 and 91 GeV, respectively; for reference, the proton mass is about 1 GeV. In 1989, the inauguration of new electron-positron colliders, SLC at SLAC and LEP at CERN, opened the precision study of the properties of these particles. At an electron-positron collider, it is possible to adjust the collision energy to equal the rest energy mc^2 of the Z^0. At this point, the probability of electron-positron annihilation has a resonance peak at which it increases by a factor of 10^3. The annihilation events in this peak are due to reactions in which a Z^0 is created and then decays to a pair of quarks or leptons. Using a variety of strategies, the experimenters can separate the events which produce each individual species of particle and measure for each the decay rate and the angular distribution. An important property of the weak interaction is that it violates parity, a fact reflected in radioactive decay of nuclei by the fact that these reactions dominantly produce electrons and neutrinos with left-handed, as opposed to right-handed, spin. This spin asymmetry leads to distinctive effects in Z^0 decays.

The coupling of the Z^0 to each species of quark and lepton is predicted by the weak-interaction theory of Glashow, Salam, and Weinberg [3, 4, 5]. This theory contains four fundamental particles—two electrically charged and two neutral—which are responsible for the weak and the electromagnetic (collectively, 'electroweak') interactions. At the basic, symmetrical level of the theory, all four particles are massless. To give mass to these particles, it is necessary to assume an additional field, existing throughout space, that sits down and chooses an preferred orientation with respect to the symmetry. This is the mysterious entity called the 'Higgs boson field'. The Higgs field gives mass to the weak-interaction bosons according to a specific pattern. The charged particles acquire mass and can be identified with the $W^\pm$. The two neutral particles mix with one another by an small amount, measured by an angle θ_w, and one of these particles remains massless. This massless state is precisely the photon. The remaining state is the Z^0, which obtains a mass slightly larger than that of the $W^\pm$ according to the relation

$$m_W/m_Z = \cos\theta_w \ . \tag{1}$$

The mixing parametrized by θ_w affects the coupling strengths of the handed quark and lepton species to the Z^0. These coupling strengths take the form

$$(I^3 - Q\sin^2\theta_w) \tag{2}$$

where I^3 equals $\pm\frac{1}{2}$ for left-handed quarks and leptons (depending on the species) and 0 for right-handed particles, and Q is the electric charge. This expression implies that the spin asymmetries of the various species differ greatly, from about 14% for the electron to 94% for the b quark. Through systematic measurements, at LEP and SLC, of the angular distributions and decay patterns of particles produced from the Z^0 [6], and through an experiment at SLC that directly measures the rate of Z^0 production separately from left- and right-handed electrons [7], these various values for the spin asymmetries are confirmed experimentally.

Equations (1) and (2) indicate that the mixing angle θ_w can be determined either from the Z^0 mass or from the couplings. The most accurate way to determine this angle is to combine a precise absolute measurement of the Z^0 mass with two quantities that are already known to part-per-million accuracy, the rate of muon beta-decay and the electromagnetic fine-structure constant. In the past two years, the LEP electron-positron collider at CERN has been calibrated to five-decimal-place accuracy (a level at which influences of the tides, the water level in Lake Geneva, and local railroad operation must be identified and subtracted) to give a very precise determination of the Z^0 resonance position [8]. The decay rate and spin asymmetry measurements for the various species give additional measurements of $\sin^2\theta_w$ to four decimal places, which provide detailed tests of the model.

The accuracy of these experiments is such that they cannot be compared without taking into account the higher-order quantum mechanical corrections to the formulae such as (1) and (2). Exotic quantum processes involving the weak interactions play an equal role with high-order quantum electrodynamics processes in the computation of these corrections. Both types of effects influence the predictions for weak-interaction rates and asymmetries at the 1% level of accuracy. Thus, the detailed comparison of different experiments which measure the parameter $\sin^2\theta_w$ can determine whether these quantum processes are actually present to the extent predicted by the theory. Though the full structure of the corrections is rather complicated, the most important effects come from the 'vacuum polarization' process, in which a Z^0 converts for a short time, by a quantum fluctuation, into a pair of electrons, quarks, or W bosons. In principle, the Z^0 could also fluctuate to a pair of heavier particles, indeed, to any particle that couples to the weak interactions. In a comparing the precision measurements, it is possible that new sources of vacuum polarization might be required to bring the data into agreement. The comparison could then give evidence for or against new particles which are not included in the textbook model.

One counterintuitive property of these quantum corrections is that heavy quarks can have an especially important effect. The corrections involving the top quark, in particular, are enhanced by the factor m_t^2/m_W^2 relative to the general 1% level of quantum corrections [9, 10]. The large size of these effects comes from the fact that the masses of quarks are also due to the Higgs boson field. The top quark, being the most massive quark known, couples most strongly to the Higgs field and, through this mediator, has a especially large influence on the properties of the Z^0. The top–Higgs interaction is not so strong that it creates bound states or other new dynamical features [11] ; it is only large enough to leave its imprint on precisely measured observables.

When the enhanced influence of a heavy top quark was discovered in the 1970's, few physicists thought that this might be an important effect. In the first systematic accounting of the top quark contributions to weak-interaction reaction rates in 1980 [12], Marciano and Sirlin guessed a value of 18 GeV for the top quark mass and wrote, 'for nonexotic values of ... m_t, the corrections ... turn out to be small'. They did not know that high-energy experimenters would be unsuccessfully searching for the top quark for the next fifteen years. When the top quark failed to show up in the first data of the Fermilab Tevatron proton-antiproton collider in 1989, it became clear that the mass of this quark was large enough that it should have a major influence on the comparison of electroweak observables. Finally, the large data samples available at the Tevatron collider in 1995 allowed the CDF and D0 experiments there to collect definite evidence for this particle and determine its mass to be about 175 GeV [13, 14].

Very recently, the CDF and D0 experiments at the Tevatron collider have announced new and more precise measurements of the mass of the top quark [15, 16, 17], yielding a value $m_t = 173.9 \pm 5.2$ GeV. The identification of top quark production is a feat in itself, since top quarks are produced in only one out of every 10^7 proton-antiproton collisions. It is a delicate balancing act to select for top quark events in a way that does not unduly bias the mass measurement. Fortunately, one can make use of the fact that a heavy top quark has a very simple decay scheme, $t \to bW^+$, in which the b or bottom quark has a mass which is quite small ($m_b = 5$ GeV) and the mass of the W is known precisely. The experiments can select events in which the t quark is produced with its antiparticle $\bar{t}$, with either the W boson from the t or the $\bar{t}$ decaying to an electron or muon and a neutrino. These events produce the relatively rare signature of an isolated charged particle plus missing, unbalanced momentum. If the other W decays to a quark-antiquark pair, the whole event leads to four quarks or antiquarks, which materialize as four collimated jets of strongly-interacting particles. The strategy, then, is to divide the observed particles into four clusters, impose the constraint that two clusters should combine to a total mass equal to m_W, add a neutrino to the observed electron or muon to form the other W, and then add a cluster to each W in such a way that the composite objects have equal mass to within the measurement accuracy. In many of these events, it is possible to identify properties of the b quark jet and thus check that the clusters are assigned correctly. It is not so easy to measure the total energy-momentum of a cluster of particles, since the energy measurement can be inefficient in many ways. However, the three mass constraints, and the constraint of total momentum conservation, act in a powerful way to force the energy measurements toward their correct values.

With these experimental results in hand, we can explore whether the particles already known suffice to give the correct contribution to the vacuum polarization effect. The possible contribution of new heavy particles to the vacuum polarization can be described by two parameters S and T [18, 19]. The parameter S measures the total size of the new set of particles; the parameter T measures the extent to which these particles violate the symmetry among the weak bosons reflected in (1). The top and bottom quarks, for example, provide only one weak-interaction multiplet, but their masses are very asymmetrical; thus, this multiplet gives a small contribution to S and a large contribution to T. The two variables are defined in such a way that a contribution of 1 unit to S or T corresponds to a 1% correction to weak interaction observables, a typical size for vacuum polarization effects. Each precision measurement is sensitive to one linear combination of S and T, and so it picks out a band in the S–T plane. The overlap of the various bands tells us the extent to which the size of the vacuum polarization effect is well determined. In Figure 1, I show the situation as it was in the summer of 1990, when only the first data from SLC, LEP, and the Tevatron were available, and as it is today. The new measurements focus in on a tiny region in the S, T plane [21].

The lines superimposed on the plot show the prediction of the minimal textbook model for various values of the masses of the top quark and the Higgs boson. We see that the value of the top quark found at Fermilab is just what is needed to reconcile the electroweak data. The vacuum polarization effect of the Higgs boson also enters this comparison. Remarkably, large values of the Higgs boson mass are excluded, and values below 200 GeV are highly favored. There is no evidence that additional new heavy particles are needed.

Is this a depressing or a hopeful sign for high-energy physics? The low value of the Higgs boson mass is certainly encouraging; it indicates that this particle might even be found in the next few years at LEP or at the Tevatron. Thinking more broadly, the pattern displayed in Figure 1 chooses sides in the most important current controversy in high-energy physics, the debate over the nature of the Higgs field. Models in which the Higgs boson is composite prefer a very heavy Higgs boson mass. Typically, they also include new particles which induce extra large positive contributions to S and T [18, 22, 23, 24]. Such effects are excluded by the data. Models in which the Higgs boson is a new elementary constituent of matter allow the low values of the mass which are preferred by the fit, and certain of these models even require it. The most ambitious models of this type, 'supersymmetric grand unified theories', require that the Higgs boson is light [25, 26]. These models contain a huge number of new particles—a heavy partner for every particle in the standard theory. Surprisingly, though, the particular species predicted by these models give very small additional contributions to the vacuum polarization [27].

The new measurements, then, put the structure of the weak interactions into focus in a way that brings the story of elementary particle physics to a state of high tension. The possibilities for what we might find around the next corner are increasingly limited. The alternatives include the simple possibility of one light Higgs boson. But they also include models whose new symmetries lead to a parade of exotic particles, and even to promised new visions of space and time. In the next decade, at the next step in accelerator energy, we will learn which of these alternatives Nature chooses.

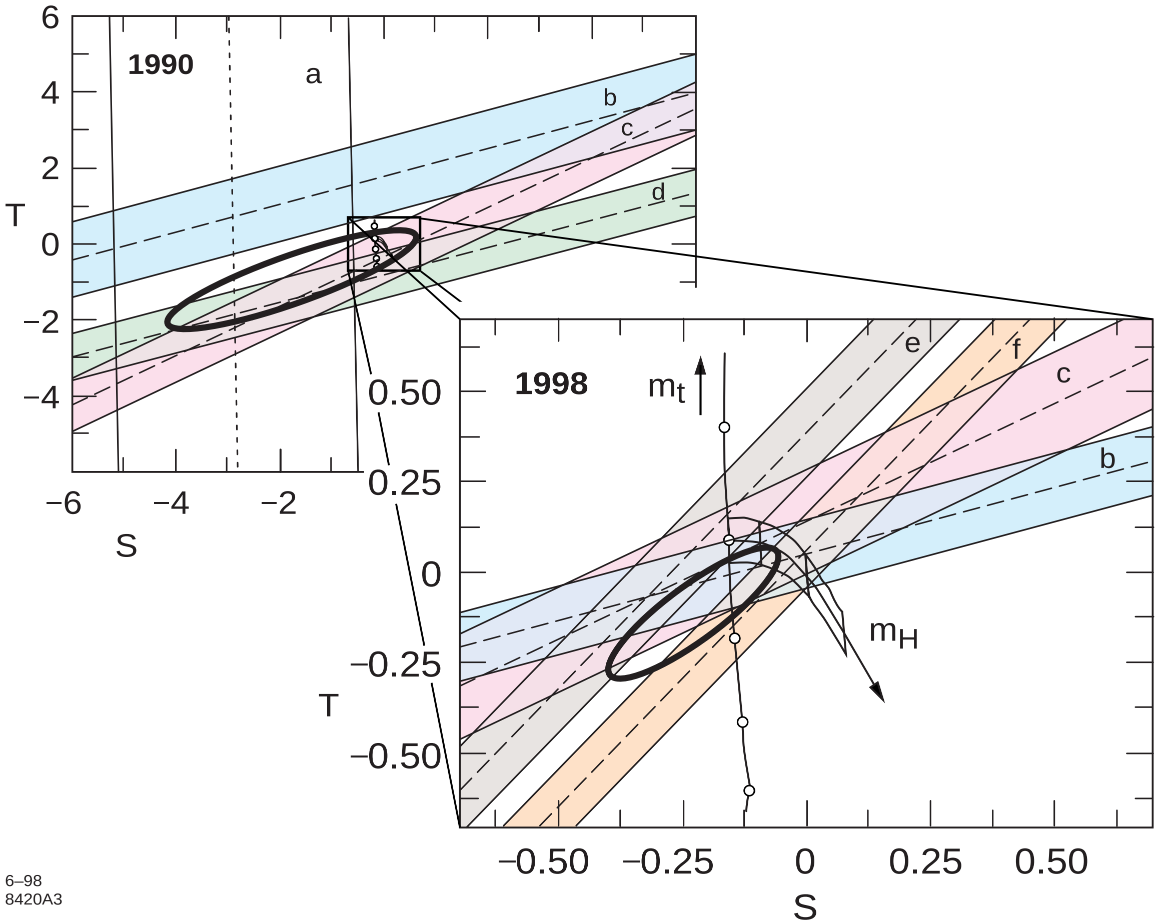

Figure 1: Fits of the corpus of weak-interaction data to the parameters S, T described in the text, using data from 1990 and 1998. The bands show the most important constraints in each data set, those from (a) atomic parity violation experiments, (b) the total decay rate of the Z^0, (c) the mass of the W, (d) neutrino scattering experiments, (e) the electron spin asymmetry, and (f) the Z^0 decay angular asymmetries. The bands show the constraints from each measurement at $\pm 1\sigma$; the ellipse shows the 68% confidence contour for the full analysis. For comparison, the flag-shaped figure shows the prediction of the textbook weak-interaction model. The vertical line shows the dependence on the top quark mass, with solid points at 25 GeV intervals. The flag shows the 1 σ error band on m_t from the Tevatron, and the dependence on the assumed mass of the Higgs boson. The vertical lines in the flag correspond to Higgs boson masses of 60, 100, 300, and 1000 GeV, from left to right. I am grateful to Morris Swartz for carrying out this analysis [20].

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