Precision in Collision: Dis

by BRUCE SCHUMM

Exacting measurements of a central parameter in the Standard Model are providing tantalizing hints that the discovery of the elusive Higgs boson may be just around the corner.

IN A 1963 LECTURE on the makings of a good scientific theory, Nobel laureate Richard Feynman compared Newton's law of gravitation to a hypothetical theory of celestial mechanics based on the influence of "oomph"— a fanciful motive quality possessed by the planets that, in its vagueness, could be deemed responsible for any observed behavior of the solar system. Newton's theory is much preferable, Feynman observed, because the smallest disagreement with its precise predictions of celestial motion could prove it wrong. For the Theory of Oomph, however, "the planets could wobble all over the place, and . . . you could say 'Well, that is the funny behavior of the oomph.' So, the more specific the rule, the more powerful it is, the more liable it is to exceptions, and the more interesting and valuable it is to check."

In exactly this spirit, two communities of physicists—one based at SLAC and another at the pan-European CERN laboratory, set out on complementary paths to test the Standard Model of particle physics with knife-edge precision. For the Standard Model, with its definitive relations between its basic physical quantities, fits Feynman's criterion to a 'T.' It stands as our leading theory of fundamental interactions, forming the very core of our current ideas about causation in the subatomic world. And, perhaps best of all, it incorporates into its structure a number of ideas that profoundly affect the way we view the world in which we live.

Foremost among the revelations suggested by the Standard Model is the notion that, for indivisible fundamental

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particles, mass is merely an illusion, induced by the swirling of eddy currents in an all-pervasive underlying field called the "Higgs" field. Hardly a theory of oomph, the existence of the Higgs field has a number of clearly predicted consequences, the most direct of these being an entirely new type of interaction between matter particles that should become appreciable as their energy of interaction gets very large. In much the same way that a game of catch between two ice skaters can cause them to drift apart, this new interaction is mediated by an exchange between the matter particles. In this case, though, the game is played with an odd sort of ball—a new particle known as the "Higgs boson," with properties unlike those of any known particle.

In 1983, as the LEP and SLC programs began construction at CERN and SLAC, the Higgs boson seemed far away indeed. The more immediate goal was to put the Standard Model through its paces with a rigorous examination of its exacting quantitative relations. In this way, the physicists hoped to find the

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smallest disagreement that would lead to the next leap forward in predictions of the Standard Model—or to rule out, by its absence, possible new paradigms of natural order dreamt up by ever-creative theoretical physicists. But, through a healthy competition between the two labs, tempered by mutual support and a free exchange of ideas and personnel, the precision of these tests has exceeded expectations to such a degree that the potential effect of the new Higgs interaction is now beginning to enter the picture.

As this article goes to press, the last chapter in this story—the compilation and combination of the finalized results of these precision tests—is nearing completion in a collaborative effort between the SLAC and CERN precision-measurement groups. The unprecedented accuracy of this combined result is providing what may be an early hint of the imminent discovery of the Higgs boson.

WHAT IS particularly amazing about these studies is their capacity to extract measurements of exquisite precision from the relative chaos of high energy particle collisions. As experimental physicists, we squint and cover our ears as potentially lethal beams of matter and antimatter collide, producing miniature explosions of a concentration not seen since the instant of the Big Bang. And yet, using our computer-aided powers of vision, we can determine certain properties of these collisions with authoritative accuracy.

At the heart of much of this experimentation lies the notion of parity violation. Consider a carefully controlled experiment that, say, measures the annihilation rate of high energy electrons and positrons into the *Z* boson—one of two possible "balls" (the other being the electrically charged *W* boson) whose exchange mediates the obscure but essential weak nuclear force. Now, consider a second, parity-inverted experiment, arranged as a mirror-reflection of the first experiment, but alike in every other way. Common sense suggests that the annihilation rate in the second experiment should be identical to that of the first, but such is not the case. In this sense, the interaction of matter with the *W* and *Z* bosons, and thus the weak interaction itself, violates symmetry under such a parity inversion.

Specifically, the aspect of the experimental setup that is altered under mirror reflection is the handedness of the incoming electrons and positrons. Electrons "spin" about their axes; if this spin is seen to be clockwise as the particle recedes from the viewer, the particle is deemed to be right-handed, while a left-handed particle spins counterclockwise. Mirror reflection preserves the sense of the electron's spinning motion while reversing the direction of its flight, thus exchanging left-handed for right-handed electrons, and vice versa.

Experiments performed in the late 1950s, interpreted in the context of today's Standard Model, demonstrate that W bosons interact exclusively with left-handed electrons: the *W* simply refuses to consort at all with right-handed electrons. So the mirror-reflection of a reaction originally involving left-handed electrons and *W* bosons will be a reaction involving *W* bosons and right-handed electrons, and is forbidden from taking place. In this sense, weak nuclear interactions mediated by the *W* boson are said to exhibit complete, or maximal, parity violation.

Such, however, is not the case for weak interactions mediated by the *Z* boson. The electrically neutral *Z* is much like a massive photon—the indivisible quantum of light that we now know to be the "ball" that is exchanged in electromagnetic interactions. However, while the photon has no preference for handedness, the weak-force *Z* boson does exhibit a preference—but only a partial one—for left-handed particles over right-handed ones.

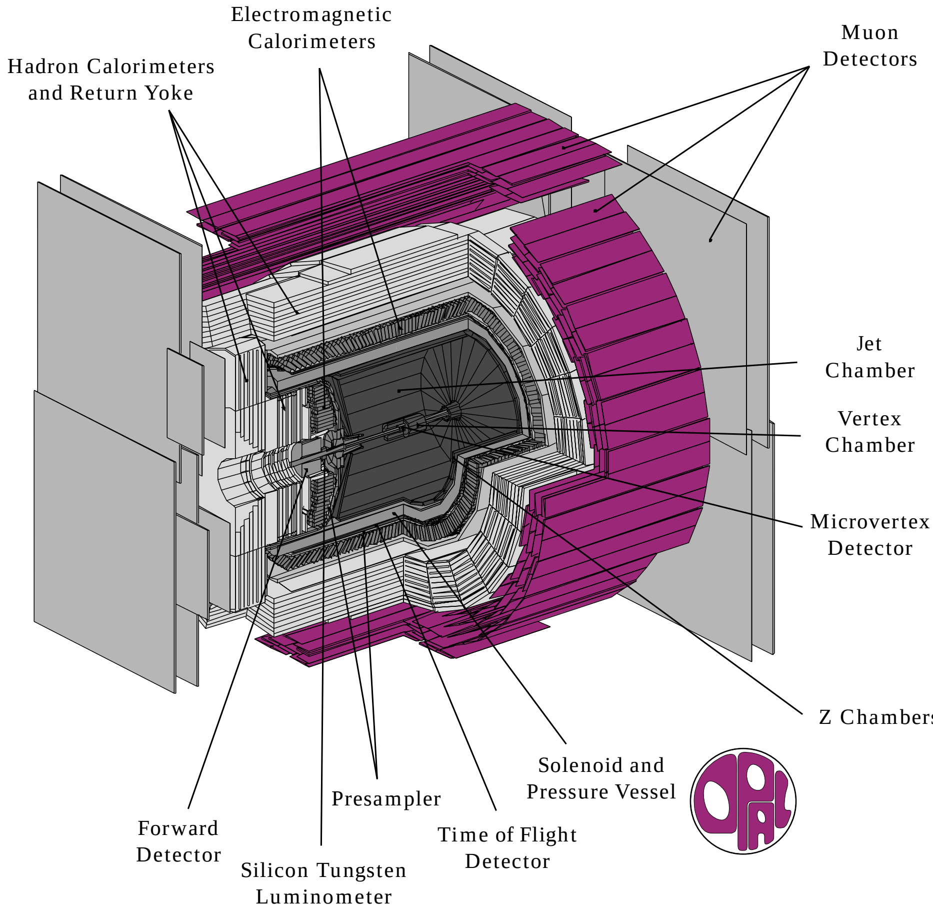
In the Standard Model the extent of this "mixing" of the parity-violating weak and parity-respecting electromagnetic interactions (to provide a weak-force mediating *Z* boson that exhibits partial parity violation) is characterized by a quantity known as the "weak mixing angle" θ_W, commonly expressed in terms of the square of its trigonometric sine: $\sin^2\theta_W$. Since the sine function (and thus also its square) varies from 0 to 1, $\sin^2\theta_W$ acts as a convenient way to express the extent to which the Z is composed of parity-respecting as opposed to parity-violating components.

For example, a value of $\sin^2\theta_W = 0$ would correspond to a Z boson made up entirely of the stuff of the parity-violating weak force. Like the W boson, such a Z boson would mediate weak interactions that violate parity completely—it would only permit left-handed matter particles to interact. In fact, though, $\sin^2\theta_W$ has a value of about 0.2, meaning that about 20 percent of its composition is electromagnetic-like. This admixture ensures that the Z will have some small degree of interest in right-handed matter particles. It thus will exhibit parity violation that is not quite complete.

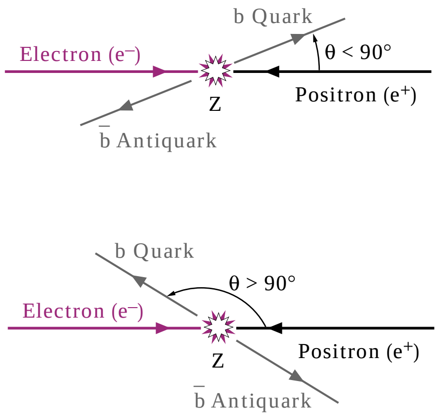
The essential point is this: once the mass of the Z boson and the overall strengths of the weak and electromagnetic forces have been determined, then $\sin^2\theta_W$, and thus the exact degree of the Z's preference for left-handed over right-handed matter particles, is precisely predicted by the formalism of the Standard Model. Exacting measurements of the relative interaction rates of the Z boson with right- and left-handed quarks and leptons comprise the most precise test ever done of the Standard Model.

DURING THE 1990s, two electron-positron colliders ran at precisely the energy necessary to produce Z bosons. Between 1989 and 1995, the Large Electron-Positron (LEP) collider at CERN produced over 15 million Z's, whose decays were recorded by the ALEPH, DELPHI, L3, and OPAL detectors. The pioneering Stanford Linear Collider (SLC) at SLAC produced just over half a million Z boson events between 1989 and 1998, recorded by the SLD detector (and the earlier Mark-II detector). Unlike LEP, however, the SLC was able to run with a preponderance of its electrons polarized either right- or left-handed, depending on the whim of a random trigger.

With their commanding data samples, the LEP experiments were quick to measure the Z boson mass by finding the precise energy at which the rate of electron-positron annihilation to the Z was greatest. This study yielded the remarkably accurate result $M_Z = 91.1874 \pm 0.0021$ GeV/c^2. Combined with even more exacting measurements of the strengths of the weak and electromagnetic forces, this result led to the prediction $\sin^2\theta_W = 0.21215 \pm 0.00001$. The stage was thus set for a precise test of the Standard Model via parity violation measurements.



The OPAL (Omni-Purpose Apparatus at LEP) detector is typical of the five detectors built at CERN to study the physics of the Z boson.



Measuring $\sin^2\theta_W$ *via the forward-backward asymmetry in the reaction* $e^+e^- \rightarrow b\bar{b}$*. If the angle* θ *between the* b *quark and the continuation of the electron's path is less than 90 degrees, the event is deemed "forward"; if* θ > 90 *degrees, the event is "backward." The difference (asymmetry) in the rates of the forward and backward reactions depends on the degree of parity violation in the interaction of the Z with both the electron and the* b *quark, and thus provides a measurement of* $\sin^2\theta_W$.

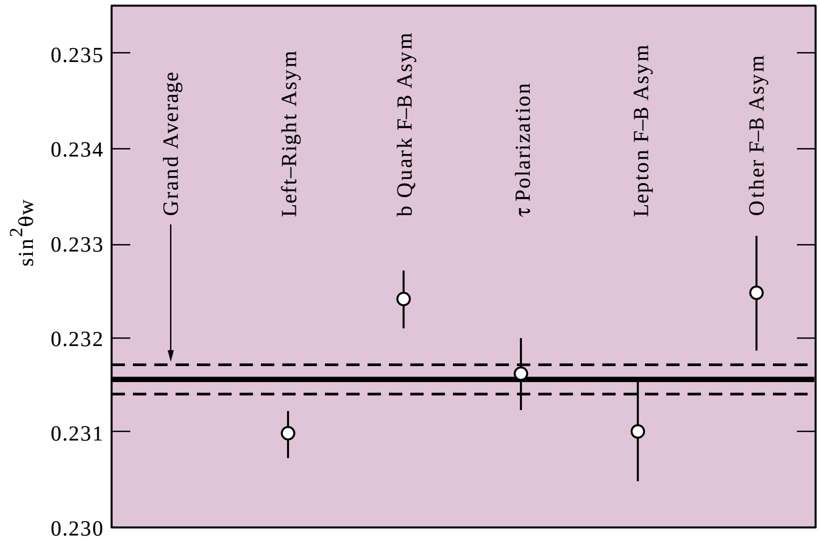
Given the relationship between handedness and parity, the most direct way to measure the degree of parity violation in the interaction of the *Z* boson with matter is to measure the difference—or asymmetry—in the production rates of the *Z* with left- and right-handed electron beams. This "left-right asymmetry" measurement has much to recommend it: the result depends very heavily on the precise value of $\sin^2\theta_W$, while its dependence on potential sources of experimental error, such as limitations in the apparatus detecting the decaying *Z* bosons, is very weak. The real challenge lies in getting the electron beam to be highly polarized—and in measuring the polarization accurately. The SLD collaboration did both of these admirably, polarizing about 75 percent of the electrons in the beam and measuring that percentage to a relative accuracy of five parts per thousand (see the Spring 1995 edition of the *Beam Line*, Vol. 25, No. 1 for an in-depth discussion of SLD's left-right asymmetry measurement). In addition to permitting the most precise measurement of $\sin^2\theta_W$ to date, both of these achievements have set new standards for electron beam polarization.

Luckily for the LEP team, there are a number of other ways to measure $\sin^2\theta_W$ that instead make use of the decay properties of the *Z* boson and do not require a polarized electron beam. The decay of the tau (τ) lepton (an unstable heavier cousin of the electron) is simple enough that it can be used to determine their handedness when they occasionally result from the decay of the *Z*. In this way, $\sin^2\theta_W$ can be measured from the handedness preference of the interaction of the *Z* with the τ lepton. A second approach is to measure the "forward-backward asymmetry"—the rate at which quarks or leptons from *Z* boson decay emerge in the same general direction as the electron beam, relative to the rate for those heading in the opposite direction (see the diagram on the left).

The precise determination of these *Z* boson properties required the development of state-of-the-art particle detectors, such as LEP's OPAL detector (see illustration on page 19). For a *Z* boson decaying into a quark-antiquark pair, about 20 charged and a similar number of neutral particles emanate from the electron-positron collision point in the center of the detector, typically in two back-to-back cones known as jets. OPAL's jet chamber reconstructs the path and momentum of each charged particle as it curls its way through the detector's magnetic field, while the vertex detector adds a few ultraprecise measurements close to the collision point so that its exact point of origin can be precisely determined. Since particles containing bottom (*b*) and charmed (*c*) quarks travel 1–2 millimeters before decaying into a multiplicity of detectable particles, this point-of-origin information can be used to identify events for which the *Z* decayed into *b* and *c* quarks. The time-of-flight and muon detectors help to establish the identity of the individual charged particles, while the layers of calorimetry determine the energy and direction of both charged and neutral particles.

For example, events with a *b* quark and $\bar{b}$ antiquark from the decay of a *Z* boson can be identified using point-of-origin information from the vertex detector. Determination of which of the two jets contains the negatively-charged b quark (as opposed to the positive $\bar{b}$ antiquark) comes from the identification of particular subatomic particles (a muon or kaon) whose negative charge establishes it as having come from a b decay. With the angle θ of the b quark's jet relative to the electron beam direction determined by the calorimetry, the excess of forward-going ($\theta < 90°$) versus backward-going ($\theta > 90°$) b quarks from Z decay—the b-quark forward-backward asymmetry—can be precisely determined.

The combined results of all these measurements, after conversion to the common currency of $\sin^2\theta_W$, yields $\sin^2\theta_W = 0.23156 \pm 0.00017$ (see the illustration at upper right). This impressive result represents a vast improvement in accuracy—by a factor of about 300—over that of measurements available prior to the beginning of the program. But when compared to the prediction $\sin^2\theta_W = 0.21215$, the disagreement is substantial!



Compiled results of parity-violation based measurements of $\sin^2\theta_W$. The left-right asymmetry measurement was performed at SLAC while the remainder were done at CERN. Note the fineness of the vertical scale, reflecting the remarkable accuracy to which these measurements have been made.

THE RESOLUTION of this apparent theoretical failure lies at the very heart of quantum mechanics, for this Standard Model prediction naively ignored the fact that—according to the Heisenberg Uncertainty Principle—the Z boson can temporarily fluctuate into a complementary pair of quarks or leptons as it mediates a weak interaction process (see the diagrams on the next page). Such "virtual pairs" slightly alter the properties of the Z boson in a way that can be precisely calculated—provided that the identity and mass of each possible participating particle is known.

In fact, when measurements of $\sin^2\theta_W$ were first becoming available from LEP in the early 1990s, one such particle—the top quark—had yet to be observed. Calculations revealed that the effect of the virtual pairs could bring the predictions of $\sin^2\theta_W$ in line with the measurements provided that the mass of the top quark lay within about 10 percent of 165 GeV/c^2. The subsequent discovery of the top quark at Fermilab in 1995, with a mass of 174±5 GeV/c^2, represented a striking triumph for the Standard Model.

Even so, one essential component of the Standard Model remains at large—the Higgs boson. Like all other particles, the Higgs boson must be taken into account in the correction for the effect of the virtual pairs, although its contribution to this effect is small. With Fermilab's top quark mass included in the virtual pair correction, the Standard Model prediction for the parity violation measurements becomes $\sin^2\theta_W = 0.2322 \pm 0.0008$, with the small uncertainty on the prediction reflecting the fact that the mass of the Higgs can be anything at all, as long as it's greater than about 110 GeV/c^2 (otherwise it would already have been discovered).

Nevertheless, today's measured value of $\sin^2\theta_W$ is even more precise

On The Web

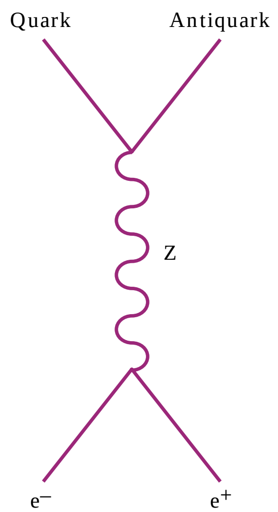
For related information on this topic refer to the following Internet addresses:

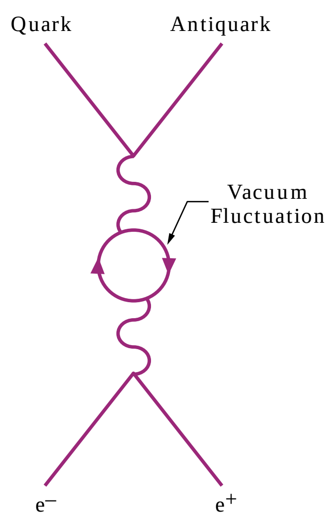
SLD
http://www-sldnt.slac.stanford.edu/alr

DELPHI
http://webnt.physics.ox.ac.uk/documents/particledemos/DelphiIntro/index.html

OPAL
http://opal.web.cern.ch/Opal

Ghostly Visits from the Higgs
http://www-sldnt.slac.stanford.edu/alr/interpretation.htm





To derive the true theoretical prediction, the possibility that the Z boson temporarily fluctuated into a matter-antimatter pair (bottom) must be included in the calculation of the basic Z-boson exchange process (top).

than this refined theoretical prediction. We can thus turn the argument around and boldly predict that when the Higgs boson is discovered, its mass will be found to be somewhere between 110 and 225 GeV/c^2. In fact, if data from other observables that can constrain $\sin^2\theta_W$ are included—such as the mass of the *W* boson (measured at Fermilab and LEP)—the allowable range for the Higgs mass is reduced somewhat, to lie between 110 and 175 GeV/c^2.

BUT THE STORY hardly ends there, for late last year, running at an energy far above that necessary to produce the *Z* boson, the four LEP experiments reported several events with decay patterns consistent with those of a Higgs boson with a mass of 115 GeV/c^2—right in line with the expectations of the precision measurements. Not quite significant enough to merit claims of discovery, this intriguing hint awaits further substantiation.

There is thus a strong suggestion, due primarily to the decade-long program of precision measurements of *Z* boson properties, that particle physics is poised on the verge of one of the most profound of its many discoveries. Expectations are running high that the Higgs boson will be conclusively uncovered either in Run II of the Fermilab Tevatron (see "What's Next in the Search for the Higgs?" by John Womersley in the Winter 2001 issue of the *Beam Line*, Vol. 31, No. 1), or within the first year of running of CERN's Large Hadron Collider, now under construction.

In the larger view, though, the likely discovery of the Higgs boson in these proton colliders may in fact lead to an even greater set of unresolved questions, for the formalism used to introduce the Higgs field into the Standard Model involves a number of ad-hoc notions, suggesting that it may be more of a step on the path towards a deeper understanding of the workings of Nature than an end in itself.

Should this be the case, a careful dissection of its properties may well provide the clues needed to propel us forward to this next level of comprehension. And if the Higgs boson indeed lies in the mass range suggested by the precision measurements, there would be no better way to pin down its properties than in the controlled environment of electron-positron collisions. The machine needed to do this—a higher energy linear electron-positron collider—is currently in its design stages, with SLAC as one of its primary proponents. Such a machine, providing an almost certain promise of important experimental results, would begin collecting data early in the next decade.