

PRECISION IN COLLISION – DISSECTING THE STANDARD MODEL

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 which, in its vagueness, could be deemed responsible for any observed behavior of the solar system. Newton’s theory, Feynman observed, is much preferable, in that 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 various basic physical quantities, fits Feynman’s criteria to a ‘T’. It also stands as our candidate theory of fundamental interactions, forming the very core of our current ideas about causation in the natural world. And, perhaps best of all, it incorporates into its structure a number of ideas that profoundly reshape 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 particles, mass is merely an illusion, induced by the swirling of eddy currents in an all-pervasive underlying ‘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 the energy of the interacting particles 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 particle known heretofore.

In 1983, as the SLC and LEP programs began their construction phases at CERN and SLAC, the Higgs seemed very 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

SLAC and CERN physicists hoped to find that ‘smallest disagreement’ that would lead to the next leap forward in our understanding of nature – or to rule out, by its absence, proposed new paradigms of natural order dreamt up by ever-creative theoretical physicists. Yet, 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 effects of the new Higgs interaction is beginning 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 lethal beams of matter and antimatter collide with each other, producing miniature explosions of a concentration not seen since the instant of the Big Bang. And yet, at the end of the day, we are able to use our computer-aided powers of sight to determine a number of the properties of these collisions with authoritative accuracy.

Lying at the heart of much of this experimentation is the notion of *parity violation*. Consider a carefully controlled experiment which, say, measures the annihilation rate of high energy electrons and positrons into the Z boson – one of the 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 dictates 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 parity inversion.

Specifically, the aspect of the experimental setup that is altered under mirror reflection is the handedness of the incoming electron and positron. Electrons spin at a well-defined rate 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 1950's, 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 interactions mediated by the Z boson. The electrically neutral Z boson is really very much like a massive photon – the indivisible quantum of light which, as a result of the work of Feynman and others in the 1940's, we now appreciate to be the 'ball' that is exchanged in the mediation of electromagnetic interactions. In fact, in its unification of the weak nuclear and electromagnetic interactions, the latter of which is known to have no preference one way or the other for handedness, the Standard Model ascribes to the weak-force Z boson only a *partial* preference for left-handed particles over right-handed particles.

The extent of this mixing of the parity-violating weak and parity-respecting electromagnetic interactions (to provide a weak-force mediating Z boson which 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 zero to one, $\sin^2 \theta_W$ acts as a convenient way to express the extent to which the Z is composed of parity-respecting (electromagnetic-like) as opposed to parity-violating (weak-force-like) 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 which violate parity completely, i.e., would only permit interactions with left-handed matter particles. In fact, though, the value of $\sin^2 \theta_W$ is about 0.2, meaning that about 20% of its composition is electromagnetic-like. This 20% admixture of the Z 's composition, which treats left- and right-handed particles with equal regard, ensures that the Z will have some small degree of interest in right-handed matter particles. It will thus will exhibit parity violation which 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 measured, 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 tests ever done of the predictions of the Standard Model.

During the decade of the 1990's, two electron-positron colliders ran at precisely the energy necessary to produce Z bosons (see Fig. 1). Between 1989 and 1995, the LEP-I storage ring collider at CERN produced over 15 million Z 's, recording their subsequent decays in its ALEPH, DELPHI, L3 and OPAL detectors. The pioneering SLC linear collider at SLAC, with its SLD detector (and earlier MARK-II detector), produced just over half a million Z boson events between 1989 and 1998. Unlike LEP, however, the 'polarized' SLC was able to run with a preponderance of its beam electrons 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 prior 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.

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 simply 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, requiring the polarized electron beam available at SLAC, has much to recommend it: it depends very heavily on the precise value of $\sin^2 \theta_W$, while its dependence on potential sources of experimental error, such as limitations of apparatus detecting the decaying Z bosons, is very weak. The challenge in doing this measurement lies in getting the electron beam to be highly polarized, and in measuring that polarization accurately. The SLD detector collaboration did both of these admirably, polarizing about 75% 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 *Beam Line* for an in-depth discussion of SLD's left-right asymmetry measurement). In addition to permitting the SLD to make the most precise measurement of $\sin^2 \theta_W$ to date, both of these achievements have set a new standard in the field of electron beam polarization.

Luckily for the LEP team, there are a number of other ways to measure $\sin^2 \theta_W$ that make use of the *decay*, rather than the production, properties of the Z boson and do not require a polarized electron beam. The decay of the τ lepton (an unstable heavier cousin of the electron) is simple enough that it can be used to determine the handedness of τ leptons which are themselves decay products 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 of quarks or leptons from Z boson decay going in the same general direction as the electron beam, relative to the rate of those going in the direction of the counter-circulating positron beam.

The precise determination of these Z boson properties required the development of state-of-the-art particle detectors, such as LEP's OPAL detector (Fig. 2). For a Z boson decaying into a quark-antiquark pair, about 20 charged and a similar number of neutral subatomic particles emanate from the electron-positron (e^+e^-) 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 ultra-precise measurements close to the e^+e^- collision point so that the particle's 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 establish the identity of the individual charged subatomic 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 (an electron 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 direction then determined by the calorimetry, the excess of forward-going ($\theta < 90^\circ$) versus backward-going ($\theta > 90^\circ$) b quarks from Z decay – the b -quark forward-backward asymmetry – can be precisely determined (see Fig. 3).

The compiled results of all these measurements, after conversion to the common currency of $\sin^2 \theta_W$ (see Fig. 4), can be averaged together, yielding $\sin^2 \theta_W = 0.23156 \pm 0.00017$. This impressive result represents an vast improvement in accuracy – by a factor of about 300 – over that of measurements available prior to the beginning of the program. On the other hand, though, this measured value can be compared to the prediction $\sin^2 \theta_W = 0.21215$ from several paragraphs above – and it disagrees substantially!

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 matter and antimatter particles as it mediates a weak interaction process (Fig. 5). 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 all possible contributing particles is known ahead of time.

In fact, in the early 1990's, when precise parity-violation measurements of $\sin^2 \theta_W$ were first becoming available, 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% of $165 \text{ GeV}/c^2$. The subsequent discovery of the top quark at Fermilab in 1994, with a mass of $174 \pm 5 \text{ GeV}/c^2$, 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 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 $110 \text{ GeV}/c^2$ (otherwise it would already have been discovered).

Nevertheless, today's *measured* value of $\sin^2 \theta_W = 0.23156 \pm 0.00017$ is yet more precise than the theoretical prediction – and again we can turn the argument around, boldly predicting, in this case, that when the Higgs

is discovered, its mass will be found to be somewhere between 25 and 225 GeV/c². In fact, if data from other observables which can measure $\sin^2 \theta_W$ are included – such as the mass of the W boson (measured at Fermilab and with a higher-energy incarnation of the LEP accelerator) – this allowable range for the Higgs mass is reduced somewhat, lying between 20 and 175 GeV/c².

But the story hardly ends here, for late last year, running at an energy far above that necessary to produce the Z boson, the four LEP experiments reported a number of collisions with decay patterns consistent with those of a Higgs boson with a mass of 115 GeV/c² – right in line with the expectations of the precision measurements. Not quite significant enough to merit claims of discovery, this intriguing hint awaits substantiation.

There is thus a strong suggestion, due primarily to the decade-long program of precision measurements of Z boson properties, that particle physics rests on the verge of one of the most profound of its many great discoveries. Expectations are running high that the Higgs will be conclusively uncovered either in RUN-II of the Fermilab Tevatron (beginning as this article goes to press), or within the first year of running of CERN's Large Hadron Collider in 2005.

In the larger view, though, the discovery of the Higgs in these proton colliders may in fact lead to an even greater set of unresolved questions, for the formalism of the inclusion of the Higgs field within 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 just the clues that are necessary to propel us forward to this next level of comprehension. And, if the Higgs 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, or 'Linear Collider' for short – is currently in its proposal stage, with SLAC as one of its primary proponents. Such a machine, providing an almost certain promise of exciting experimental results, would be expected to begin collecting data towards the end of this decade.

All in all, though, you'll want to keep your ear to the tracks, for the first decade of the new millennium may well be a rewarding time during which to

follow developments in particle physics!