FIVE PHASES OF WEAK NEUTRAL CURRENT EXPERIMENTS
FROM THE PERSPECTIVE OF A THEORIST

Paul Langacker
University of Pennsylvania
Department of Physics
Philadelphia, Pennsylvania, USA 19104-6396
October 21, 2018, UPR-0553T, hep-ph/9305255

Abstract

I give my personal perspective on the past, present, and future of weak neutral current experiments, emphasizing the experimental inputs; the theoretical difficulties and inputs; the role of model independent and global analyses; and the implications at each stage.

• Introductory Comments
• The Discovery Phase (unification)
• The Second Generation (the standard model confirmed)
• The Third Generation (precision tests; radiative corrections)
• The LEP Era (high precision; \( m_t \); new physics searches)
• The Future (complement to colliders)

---

1Invited talk presented at 30 Years of Neutral Currents. From Weak Neutral Currents to the (W)/Z and Beyond, Santa Monica, February 1993.
1 Introductory Comments

I have been interested in the implications of weak neutral currents for some 17 years. In this talk I will describe the five major phases of experiments from my own theoretical point of view. Let me begin with some general comments.

- The weak neutral current (by which term I include the properties of the \( W \) and \( Z \) bosons) has always been the primary test of the electroweak unification. QED and the weak charged current theory already existed and were incorporated into the standard model. (The latter was, however, greatly improved by the possibility of computing radiative corrections.)

- The weak neutral current experiments have uniquely established the fermion couplings, consistent with the gauge group and fermion representations of the standard model.

- The weak neutral current has also probed the underlying structure of gauge field theory. The electroweak unification in itself is a significant success of the gauge concept. Furthermore, the precision experiments require the calculation of radiative corrections, which tests the whole concept of gauge invariance and renormalization theory. The electroweak unification has also made possible the calculation of finite higher-order corrections to weak charged current processes, which are essential for agreement between theory and experiment.

- Another role has been the search for new physics. So far all data are in agreement with the standard model. Moreover, there are large domains of possible new physics which are excluded. I expect that this role will continue to be significant in the future, and that precision experiments will be a useful complement to high energy colliders.

- I would also like to emphasize the complementarity of the various precision experiments. No one experiment is sensitive to every type of new physics or to every aspect of the standard model. However, because of the wide variety of reactions and kinematic ranges that have been explored it is unlikely that any relevant type of new physics would be able to slip through without leaving a signature.

- The program has been aided by the global analysis of all experiments simultaneously. A global analysis has the advantage that the experiments collectively contain more information than any one, but has the obvious caveat that one must be careful in the estimation and application of experimental and theoretical uncertainties and their correlations.
2 The Five Phases

Let me first give a brief overview of the five phases.

- The discovery phase, which culminated in 1973 with the discovery of the weak neutral current, has been extensively discussed at this conference. In particular, the existence of the weak neutral current was a successful prediction of the $SU_2 \times U_1$ model.

- The second generation of experiments occurred in the latter half of the 1970’s, and was dominated by purely weak $\nu N$ and $\nu e$ scattering, and by weak-electromagnetic interference in the polarized $e^+D$ asymmetry from SLAC. These experiments were sufficiently precise (typically $\sim 10\%$) that it was possible to begin model-independent fits, which means an analysis allowing for an arbitrary gauge theory. It was possible to determine most of the vector and axial parameters of the four-Fermi interactions and to show that they were consistent with the $SU_2 \times U_1$ model to first approximation, and not some completely different theory. Assuming the standard model, one was able to obtain a reasonably precise value for the weak angle, $\sin^2 \theta_W = 0.229 \pm 0.010$, where the error was mainly experimental. Although it was not presented in this way, the results implied an upper limit of $m_t < 290$ GeV.

- The third generation of experiments, in the 1980’s, was characterized by higher precision (typically 1 – 5%) and the existence of many more probes. These included purely weak $\nu N$ and $\nu e$ scattering, as well as a number of weak-electromagnetic interference phenomena. New results included atomic parity violation, $e^+e^-$ annihilation, and the actual observation of the $W$ and $Z$ bosons at CERN with a determination of their masses. The result was that the standard model was correct, and complicated alternative models (with similar four-Fermi interactions) were excluded. Furthermore, for the first time the weak interactions of the $b$ quark were measured in both charged and neutral current processes, with the consequence that the $t$ exists, and searches were made for and limits set on many types of new physics. A more precise value of the weak angle was obtained, $\sin^2 \theta_W = 0.230 \pm 0.007$, where now the error was mainly theoretical from the interpretation of deep inelastic scattering. One obtained a more stringent limit $m_t < 200$ GeV.

- The fourth phase is the LEP era, which began in 1989. This is dominated by the $Z$-pole observables including $M_Z$ and the $Z$ widths and asymmetries, which are typically at the few tenths percent level. There have also been a number of other experiments, including much improved measurements of $M_W$, atomic parity violation (APV), and more precise $\nu e$ scattering. They test the standard model at the level of radiative corrections and stringently search for new physics. The weak angle is now determined an order of
magnitude better than before, \( \sin^2 \theta_W(M_W) = 0.2328 \pm 0.0007 \), where now the error is almost entirely due to the uncertainty in \( m_t \). One also has the standard model prediction \( m_t = 150^{+19+15}_{-24-20} \) GeV, where the second error is from the Higgs mass.

- Finally, there is the possibility of future ultrahigh precision (\( \ll 1\% \)) experiments. These include polarization asymmetries, much improved atomic parity violation experiments, determinations of \( M_W \), and a possible \( \nu N \) experiment at Fermilab. These experiments would be sensitive to many types of new physics up to the TeV range and would be a useful complement to the direct searches for new particles at the SSC and LHC.

3 The Discovery Phase

I don’t have much to say about this phase from personal experience. (I was working on completely different things at the time.) Nevertheless, I would like to make a few comments.

- It is important to recall the historical context. The discovery of the weak neutral current occurred during the period of – and was in part responsible for – a complete change of outlook in particle physics. Previously, the emphasis had been on the classification of elementary particles and their properties, and most effort was devoted to the strong interactions and \( S \)-matrix theory. Gradually, however, the framework changed to quantum field theory. This change was effected by theoretical developments, the parallel development of quarks and QCD, and of course the discovery of the weak neutral current.

The original role of the flavor-changing neutral currents (FCNC) can be characterized as looking under the wrong lamppost. As we have heard at this meeting, the severe limits on the FCNC confused the issue because it was reasonable to expect that if they were small then the flavor-conserving interaction should also be small. Furthermore, their absence delayed the theoretical development of the hadronic part of the standard model, which required the GIM mechanism \([1]\). But this needed the charm quark, which people were reluctant to accept until the discovery of the \( J/\psi \) and neutrino-induced dimuons. FCNC are now very important again, because they are predicted at some level by most extensions of the standard model. In particular, theories involving compositeness and/or dynamical symmetry breaking generally predict FCNC far in excess of the existing limits. The experimental limits have severely held up the development of realistic models, and perhaps even cast doubt upon that whole set of ideas. It is important to push the searches as far possible, not only in the kaon system, but also in heavy quark and lepton decays.
• The weak neutral current has always been closely connected with the uni-
fication of the weak and electromagnetic interactions. Almost all unified
theories predict neutral currents, and, conversely, the most natural way to
have neutral currents is within gauge unification. Furthermore, neutral cur-
rents (or the ratio of neutral current and charged current rates) have always
been the primary quantitative test of the structure of the standard model
and have been crucial in the search for new physics.

The Fermi theory of the weak charged current and QED existed before the
unification. They were incorporated, and the Fermi theory was improved
in the sense that unification made possible the calculation of higher-order
corrections. Nevertheless, the weak charged current has so far been less
important in establishing the standard model and searching for new physics.
This is due in part to the fact that charged current experiments tend to
have more hadronic uncertainties. Furthermore, precise measurements often
result in the measurement of an element of the CKM mixing matrix [2] ra-
ther than directly testing the standard model. Of course, verification that
the CKM matrix is unitary is important. For example, the successful relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992 \pm 0.0014$$

(1)

eliminates many extensions of the standard model involving right-handed
currents or extended fermion sectors. This success is particularly remarkable
in that if one did not apply radiative corrections to $\beta$ and $\mu$ decay one would
have obtained 1.036, in contradiction with unitarity. Without the entire
apparatus of non-abelian gauge theory one would not have been able to
calculate these corrections, which would have been infinite and meaningless,
so (1) tests the underlying ideas of gauge theory. In the future we expect
other important probes of CKM unitarity, especially CP violation in $B$
decays. Nevertheless, the neutral current has so far been the most important
test of the standard model.

• As we have heard at this meeting there were many early confusions. Weak
interaction experiments are hard, and incorrect results are sometimes ob-
tained. There is a long history of this in charged current interactions, neu-
trino mass, etc., and the neutral current is no exception. Incorrect early
results significantly delayed the discovery of the weak neutral current. Even
after it was found the confused situation for the first few years, such as
unsuccessful searches for atomic parity violation, led to a plethora of alter-
native theoretical models. This takes me to the second phase.
4 The Second Generation

The second generation of experiments in the second half of the 1970’s, which were typically of 10% precision, clarified the situation. In particular, they established that the basic structure of the standard model was correct, at least for the 4-Fermi interactions relevant at low energies, and many alternative models with disjoint parameters were eliminated [4].

4.1 The Experiments

Most of the experiments were purely weak processes involving the neutral current scattering of neutrinos. The most precise were the CERN and Fermilab measurements of deep inelastic scattering, $\nu N \rightarrow \nu X$, from targets that were approximately isoscalar. Although these gave the most precise results, if one wanted to independently determine the isospin structure of the neutral current one needed other information, such as could be provided by deep inelastic scattering from $p$ and $n$ targets, elastic scattering $\nu p \rightarrow \nu p$, and inclusive and exclusive pion production $\nu N \rightarrow \nu \pi X, \nu \pi N$. There were also several (low statistics) measurements of $\nu e \rightarrow \nu e$. This era also featured the seminal SLAC polarized $\mu \downarrow D \rightarrow e X$ asymmetry measurement [5], which established parity violation in the weak neutral current. The first successful atomic parity violation experiments in bismuth and thallium were reported towards the end of this period. There had been several early incorrect null experiments, as well as considerable theoretical difficulty in the interpretation; therefore, atomic parity did not play a significant roll in this phase. (The null experiments made even more significant the SLAC asymmetry measurement.)

4.2 Theoretical Inputs

Due to the variety of competing models it was important to have a general way of analyzing the data to distinguish between them. Each model had its own set of parameters and it was awkward to describe experimental results in terms of the parameters of each of several models. Therefore, the idea of model independent analyses of 4-Fermion couplings was devised, and was especially emphasized by Bjorken and by Hung and Sakurai [6]. One utilizes a parametrization in which each 4-Fermi interaction allows arbitrary admixtures of $V$ and $A$ coefficients for the electrons and quarks (one assumes a $V - A$ coupling for the neutrinos), as is valid for an arbitrary gauge theory. Each individual gauge model would give specific predictions for these coefficients. One then attempts to determine them from experiment in a model independent way to see which models are allowed or excluded.

$S$, $P$, and $T$ couplings are not generally included in the model independent analyses. Even today, one could not rigorously exclude significant amounts of $S$,
P, and T from the $\nu N$ and $\nu e$ reactions. However, they are rendered largely superfluous by the successes of the standard model and the discovery of the Z boson. Furthermore, the SLAC asymmetry and (in later generations) other measurements sensitive to weak-electromagnetic or neutral-charged current interference excluded the possibility of a dominant role for S, P, and T. In the interest of simplicity and for lack of theoretical motivation, we will therefore ignore the possibility of S, P, and T except as a small perturbation.

In the mid 1970’s there were reported anomalous trimuon events by the HPW $\nu N$ experiment at Fermilab. Although these did not ultimately survive, they stimulated several groups to develop alternative gauge models to account for them. I was guilty of some of this work myself, and my interest in neutral currents came about from looking for ways to constrain or test these alternative models. By that time the experiments were getting quite accurate, and I decided that it would be useful to gather all of the neutral current data and carry out a model independent analysis. For this one needs enough constraints to determine all of the couplings, and this in turn requires a simultaneous (global) analysis of all of the data. Another thing that was needed at that stage was a better theoretical treatment of the reactions. In particular, the deep inelastic data was becoming sufficiently precise that simple parton model expressions were no longer adequate. It became clear to my collaborators and me [4] that it would be necessary to apply QCD corrections, $c$ thresholds, etc., uniformly to all of these experiments to obtain reliable theoretical formulas from which to extract information about the weak interactions.

### 4.3 A Digression: Global Analyses of Data

The application of global analysis techniques is now well accepted, but was somewhat controversial at the time of the second generation of experiments. A global analysis is basically the combination of two or more measured numbers, which may be obtained in the same or different experiments, to obtain a result. A global analysis often contains more information than any one experiment, but care must be taken with uncertainties.

Often one applies a global analysis without using that language. For example, in QED one obtains $\alpha$ to a very high precision from the quantum Hall effect. However, that by itself does not test QED. To do so one must simultaneously analyze one or more other measurements, such as of the muon anomalous magnetic moment, $g_{\mu} - 2$. QED is tested by their consistency, e.g., by using the result of one experiment to predict another within the QED framework.

In the standard model weak neutral current sector the results of any one experiment can usually be accommodated by choosing the value of the weak angle $\sin^2 \theta_W$. However, the large (unknown) value of $m_t$ means that it plays a significant role in the radiative corrections. Therefore, any complete extraction of standard model parameters requires at least two measurements. However, even
here one is not really testing the standard model\footnote{There may, of course, be ranges of experimental values that cannot be described by \emph{any} values of \( \sin^2 \theta_W \) and \( m_t \).}; one needs to determine these two parameters and then predict the results of a third experiment. In fact, one wants to have as many different measurements as possible. Each experiment has different dependences on the parameters and on the various types of new physics, and one wants to maximize the sensitivity. Of course, if any deviation is observed one would want to have as many independent probes as possible to confirm it and to diagnose its origin out of the enormous variety of possible types of new physics.

Another advantage of a global analysis is that it allows one to determine the parameters for larger classes of models, such as arbitrary gauge theories. Once the generalized parameters are determined one can see whether the standard model is uniquely selected and set limits on small perturbations around it.

Finally, there are often different experiments measuring similar things, such as deep inelastic scattering. It is important not only that one use the best possible theoretical expressions in the analysis but that they be applied uniformly. For example, it is desirable to use the same quark distribution functions for each experiment, and crucial that common theoretical uncertainties are properly correlated.

On the other hand, there are obvious dangers when one combines experiments. In particular, one must be careful with systematic and theoretical uncertainties and the correlations between measurements. Because of the importance of careful error estimation and combination I would like to emphasize what I consider the four mortal sins of data presentation:

- The first is to underestimate systematic or theory errors.
- The second, and almost as serious, is to overestimate systematic or theoretical errors. The old idea of multiplying an uncertainty by \( \pi \) may be reasonable for giving an absolute bound on the range of errors, but it can be misleading if one tries to use the quoted uncertainty quantitatively. Based on my own observation of experiments and how they have compared with later more precise results, I suspect that there has been a tendency to overestimate systematic errors.
- A third mortal sin is to not publish error correlation matrices.
- Finally, it is important to not present experimental results in too narrow or trendy a context. For example, it is more useful to publish observables (such as cross sections) which can be interpreted or analyzed in the context of a general gauge theory (or, hopefully, an even more general framework), rather than just \( \sin^2 \theta_W \). Such results can be interpreted in a wider context, can be more readily used for setting limits or searching for new physics, and can be later updated if the theoretical calculations of strong interactions effects,
radiative corrections, etc., are improved. Obviously, detector dependent-artifacts, acceptances, etc., have to be corrected for. One can present results both in this form and in terms of \( \sin^2 \theta_W \).

### 4.4 Results

There were several global analyses of the second generation of the experiments. I will report on those in the article by Kim et al. [4].

- Model independent analyses of the 4-Fermi couplings were carried out. The couplings relevant to \( \nu q \) and \( \nu e \) interactions were uniquely determined for an arbitrary \( V \) and \( A \) theory (assuming \( V - A \) neutrino couplings and family universality), while the \( \nu e \) couplings were determined up to a two-fold ambiguity. The results are shown in Figures 1, 2, and 3 and in Table 1. Many alternative models with disjoint predictions for these couplings were eliminated.

- Assuming the standard model, one had a rather precise value for the weak angle, namely \( \sin^2 \theta_W = 0.229 \pm 0.010 \). Also one had a result on the parameter \( \rho_0 \equiv M_W^2 / M_Z^2 \cos^2 \theta_W \), which could be interpreted as an upper limit \( m_t < 290 \) GeV. The \( \sin^2 \theta_W \) error was dominated by experimental uncertainties, although the theoretical uncertainties were not negligible.

At about the same time grand unified theories, e.g., based on the \( SU_5 \) model, became popular, which predicted \( \sin^2 \theta_W = 0.209^{+0.003}_{-0.002} \). The experiments were already precise enough to be problematic for these models [7], even before the nonobservation of proton decay. Within a year or two several groups [8] pointed out that supersymmetric extensions of the standard

---

3Such corrections are usually model dependent. However, these may be calculated assuming the standard model, which we now know to be an excellent first approximation. Similar statements apply to many radiative corrections.
Figure 1: Allowed regions for the couplings relevant to neutrino quark interactions in 1981, from [4]. Only the cross hatched regions are allowed by all of the data. The left and right chiral couplings to the up and down quarks are defined by the effective interaction

\[ -L^\mu N = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma_\mu (1 - \gamma_5) \nu J^\mu H, \]

where

\[ J^\mu H = \sum_i [\epsilon_L(i)\bar{q}_i\gamma^\mu (1 - \gamma_5)q_i + \epsilon_R(i)\bar{q}_i\gamma^\mu (1 + \gamma_5)q_i]. \]

In the standard model the couplings are predicted at tree-level to be

\[ \epsilon_L(u) \simeq \frac{1}{2} - \frac{2}{3}\sin^2 \theta_W, \quad \epsilon_R(u) \simeq -\frac{2}{3}\sin^2 \theta_W, \]

\[ \epsilon_L(d) \simeq -\frac{1}{2} + \frac{1}{3}\sin^2 \theta_W, \quad \text{and} \quad \epsilon_R(d) \simeq \frac{1}{3}\sin^2 \theta_W. \]

The angles \( \theta_{L,R} \) are measured with respect to the vertical (\( \epsilon_{L,R}(d) \)) axes.
Figure 2: Leptonic coupling constants allowed at 90% confidence level in 1981, from [4]. The vector and axial vector couplings are defined by $-L^\nu e = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma_\mu (1 - \gamma_5) \nu \bar{e} \gamma^\mu (g_V^e - g_A^e \gamma_5) e$. In the standard model, $g_V^e \simeq -\frac{1}{2} + 2 \sin^2 \theta_W$, $g_A^e \simeq -\frac{1}{2}$.
Figure 3: Regions allowed by the SLAC and early atomic parity violation experiments in 1981, from [4]. The parity violating couplings are defined by

\[ L_{PV}^{eq} = \frac{G_F}{\sqrt{2}} \sum_i \left[ C_{1i} \bar{e} \gamma^\mu \gamma_5 e \bar{q}_i \gamma_\mu q_i + C_{2i} \bar{e} \gamma^\mu e \bar{q}_i \gamma_\mu \gamma_5 q_i \right]. \]

In the standard model, \( C_{1u} \simeq -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W \), \( C_{1d} \simeq \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \), \( C_{2u} \simeq -C_{2d} \simeq -\frac{1}{2} + 2 \sin^2 \theta_W \).
model, such as SUSY $- SU_5$, led to a larger prediction $0.225^{+0.015}_{-0.002}$, in good agreement with experiment. This is illustrated in Figure 4.

- There were also early limits on additional heavy $Z'$ bosons.

5 The Third Generation

The third generation of experiments in the 1980’s were of the 1 – 5% level. They not only made more precise the statement that the standard model is correct to first approximation, but they also ruled out many epicycle models which reproduced the low energy 4-Fermi interactions but involved different $W$ and $Z$ masses. These experiments were also the first to see the effects of radiative corrections in a significant way.

5.1 The Experiments

This generation included high precision $\nu N$ and $\nu_\mu e$ experiments at CERN, Fermilab, and elsewhere, and also the first $(\bar{\nu}_e)\nu_e e$ experiments at the Savannah River reactor and at LANL. The latter were sensitive to interference between the neutral and charged currents. Furthermore, there are many measurements of weak-electromagnetic interference, from PEP, PETRA, and TRISTAN below the
$Z$-pole, including $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, and hadrons. A new generation of precise atomic parity violation experiments in the cesium atom were performed in Paris and Boulder. Not only were the experiments much better, but cesium is a simple atom with a single valence electron outside a tightly bound core, allowing a clean calculation of the relevant atomic theory. There was also a $\mu C$ asymmetry experiment at CERN. Finally during this era the $W$ and $Z$ were directly produced and observed at CERN and later at Fermilab, and their masses determined.

5.2 Theoretical Inputs

The new higher precision required a careful attention to radiative corrections and to the definitions of the renormalized weak angle $\sin^2 \theta_W$. Marciano and Sirlin [9] and others carried out careful calculations of the corrections to all relevant 4-Fermi processes. Another necessary input was a more careful evaluation of the theoretical formulas for deep inelastic scattering. This was greatly helped by an analysis of Llewellyn-Smith [10], who used isospin arguments to show that most of the structure function uncertainties (other than those associated with the $c$-quark threshold and non-isoscalar targets) cancelled in the ratio of neutral and charged current cross sections. During the mid-1980’s, I spent a great deal of time reanalyzing all of the deep inelastic experiments to estimate the remaining corrections and their uncertainties. Each experimental collaboration had done their own analysis, but had usually only extracted $\sin^2 \theta_W$. For a model independent analysis one needs a more general expression. It was necessary to reanalyze all of the experiments, folding in the appropriate cuts, acceptances, and spectra. The model independent reanalysis also allowed one to apply uniform theoretical expressions to all of the experiments and to properly correlate the theoretical uncertainties [11].

Another theoretical input was a parameterization of the effects of certain types of new physics, such as $Z'$ bosons [12], exotic fermions which mix with the ordinary fermions [13], etc. One needs an explicit parametrization of how they affect each observable. This should be fairly general and not tied to a specific model, but on the other hand there must be a small enough number of parameters to be manageable. One would also like the parameters to have clear physical meanings, such as masses and mixing angles of physical particles.

5.3 Results

These experiments were interpreted in a global analysis by Amaldi et al. [11] in 1987, in a theoretical collaboration which consisted of three theorists and five experimenters. There was no evidence for any deviation from the standard model: it is correct to first approximation, and many contrived models with unusual values

---

4It was just possible for an outsider to reanalyze this generation of experiments. That could never be done with the more complicated LEP experiments.
Figure 5: Current allowed regions for the neutrino quark couplings, including results published since 11.

Figure 6: Current status of the $\nu e$ parameters, including the recent CHARM-II results 14. The $\nu_e e$ data allow four solutions, which differ by the interchange of $V$ and $A$ and an overall sign difference. The $\nu_e e$ data eliminates two of these solutions. The vector-dominant solution is eliminated by $e^+ e^-$ annihilation data under the additional (by now plausible) assumption that the interaction is dominated by the exchange of a single $Z$ boson.

for the gauge boson masses were eliminated. The model independent analyses were repeated and improved. There were unique values for the 4-Fermi parameters relevant to $\nu q$, $\nu e$, and $e q$ scattering, as can be seen in Figures 5, 6, and 7. These also featured considerably smaller error bars than in the previous analyses (Figures 1–3 and Table 1.)

The interferences between weak and electromagnetic couplings observed in $e^+ e^-$ and $e q$ processes show that they are not purely $S$, $P$, and $T$. (This was already shown in the $e q$ system by the SLAC asymmetry.) Similarly, the $\nu_e e$ interaction is not $S$, $P$, $T$ because of the observed interference between charged and neutral currents. (This also shows that the $\nu_e e$ interaction is flavor conserving at the neutrino vertex. It is the only evidence in that sector 15.) Strictly speaking, there is no proof that the $\nu q$ interactions are vector and axial, but by applying Occam’s Razor it is reasonable to assume that they are not dominated by $S$, $P$, $T$. 

15
Figure 7: Regions of the parity-violating $eq$ interaction currently allowed by atomic parity violation, the SLAC asymmetry, and the combined fit, compared with the predictions of the standard model.

and $T$ (especially following the discovery of the $W$ and $Z$).

By this period it was clear that radiative corrections are necessary to account for the data, particularly the values of the $W$ and $Z$ masses compared to the neutral current processes. The value of the weak angle $\sin^2 \theta_W = 0.230 \pm 0.007$ was now established more precisely than before, with the uncertainties now mainly theoretical, dominated by uncertainties in the $c$ quark threshold in deep inelastic scattering.\footnote{The uncertainty is mainly in charged current scattering, but the relevant quantity is the ratio of neutral to charged current cross sections.} From the collection of data one could set a robust upper limit $m_t < 200 \text{ GeV}$ on $m_t$.

Another consequence of this generation of experiments, including neutral current, charged current, and gauge boson properties, was that (assuming the standard model gauge group and reasonable assumptions) the fermion assignments of all of the new fermions could be determined uniquely \cite{16}. That is, the left-handed particles occur in doublets and the right-handed particles in singlets. In particular, measurements of the weak interactions of the $b$ imply that the $t$ exists. This is a compelling argument based directly on experimental data, which complements theoretical arguments involving anomalies. Similarly, the properties of the $\tau$ imply that the $\nu_\tau$ must exist.

The more precise coupling constants allowed a cleaner test of grand unification, as can be seen in Figures \ref{fig:diagram} and \ref{fig:diagram2}. The results again show that ordinary $SU_5$ and similar models are excluded, while the supersymmetric extensions are in good agreement with the data, “consistent with SUSY GUTS and perhaps even the first harbinger of supersymmetry” \cite{11}.

Finally, there were stringent limits placed on many types of new physics during this period, such as the masses and mixings of heavy $Z'$ bosons, the mixings of exotic fermions with unusual weak interactions, exotic Higgs fields (Figure \ref{fig:diagram3}), leptoquarks, and 4-Fermi operators.
Figure 8: Predictions of ordinary and supersymmetric grand unified theories for $\sin^2 \theta_W$ and $m_t$ compared with the data in 1987. Based on the analysis in [11].
Figure 9: Constraints on $\rho_0$ vs $\sin^2 \theta_W$ in 1987, from [11]. $\rho_0$ is predicted to be one in the minimal standard model but could differ from unity in models with Higgs triplets, etc. The different constraints from the various experiments illustrate the power of a global analysis in giving more stringent results than any one experiment. The curves shown assume $m_t < 100$ GeV. For more recent results and the effects of a larger $m_t$, see [17].
6 The LEP Era

LEP has been running since 1989, bringing us into a much more precise era of precision tests. Typical results are in the 0.1% range, where the radiative corrections are essential. One stringently tests the standard model, constrains $m_t$, and searches for small perturbations due to new physics.

6.1 The Experiments

The four LEP experiments – ALEPH, DELPHI, L3, and OPAL – have measured the $Z$ mass to the amazing precision of $M_Z = 91.187 \pm 0.007$ GeV, and have made excellent measurements of the various widths and asymmetries, such as $\Gamma_Z$, $\Gamma_{f\bar{f}}$, $A_{FB}(f)$, $A_{pol}(\tau)$ \cite{18}. Recently the SLD collaborations \cite{19} at the SLC have made the first measurement of the polarization asymmetry $A_{LR}$. Many of the current observables are shown in Table 2 along with their standard model predictions. There are also new precise measurements of $M_W$ from CDF \cite{20}, $M_W/M_Z$ from UA2 \cite{21}, the weak charge $Q_W$ in cesium \cite{22}, and a new generation of $\nu_\mu e$ scattering from CHARM II \cite{14}.

6.2 Theoretical Inputs

An enormous effort was needed to accurately calculate the radiative corrections to $e^+e^-$ annihilation in the vicinity of the $Z$-pole. This was carried out by a number of groups, mainly in Europe. Much effort has also gone into parametrizations of small deviations from the standard model.

6.3 Results

- Precision standard model tests and $m_t$: there is no evidence for deviation from the standard model for wide range of probes and distance scales, in-
| Quantity         | Value                        | standard model |
|------------------|------------------------------|----------------|
| $M_Z$ (GeV)      | 91.187 ± 0.007               | input          |
| $\Gamma_Z$ (GeV)| 2.491 ± 0.007                | 2.490 ± 0.001 ± 0.005 ± [0.006] |
| $R = \Gamma_{had}/\Gamma_{l\bar{l}}$ | 20.87 ± 0.07            | 20.78 ± 0.01 ± 0.01 ± [0.07] |
| $\sigma_p(nb)$  | 41.33 ± 0.18                 | 41.42 ± 0.01 ± 0.01 ± [0.06] |
| $\Gamma_{bb}$ (MeV)| 373 ± 9                   | 375.9 ± 0.2 ± 0.5 ± [1.3] |
| $A_{FB}(\mu)$   | 0.0152 ± 0.0027             | 0.0141 ± 0.0005 ± 0.0010 |
| $A_{pol}(\tau)$ | 0.140 ± 0.018                | 0.137 ± 0.002 ± 0.005 |
| $A_c(P_t)$       | 0.134 ± 0.030                | 0.137 ± 0.002 ± 0.005 |
| $A_{FB}(b)$      | 0.093 ± 0.012                | 0.096 ± 0.002 ± 0.003 |
| $A_{FB}(c)$      | 0.072 ± 0.027                | 0.068 ± 0.001 ± 0.003 |
| $A_{LR}$         | 0.100 ± 0.044                | 0.137 ± 0.002 ± 0.005 |
| $\Gamma_{l\bar{l}}$ (MeV) | 83.43 ± 0.29    | 83.66 ± 0.02 ± 0.13 |
| $\Gamma_{had}$ (MeV) | 1741.2 ± 6.6          | 1739 ± 1 ± 4 ± [6] |
| $\Gamma_{inv}$ (MeV) | 499.5 ± 5.6            | 500.4 ± 0.1 ± 0.9 |
| $N_\nu$         | 3.004 ± 0.035               | 3              |
| $\tilde{g}_A$    | −0.4999 ± 0.0009            | −0.5           |
| $\tilde{g}_V$    | −0.0351 ± 0.0025            | −0.0344 ± 0.0006 ± 0.0013 |
| $s^2_W(A_{FB}(q))$ | 0.2329 ± 0.0031          | 0.2328 ± 0.0003 ± 0.0007± ? |
| $M_W$ (GeV)      | 79.91 ± 0.39                | 80.18 ± 0.02 ± 0.13 |
| $M_W/M_Z$       | 0.8813 ± 0.0041             | 0.8793 ± 0.0002 ± 0.0014 |
| $Q_W(Cs)$       | −71.04 ± 1.58 ± [0.88]      | −73.20 ± 0.07 ± 0.02 |
| $g^e_A(\nu e \rightarrow \nu e)$ | −0.503 ± 0.017  | −0.505 ± 0 ± 0.001 |
| $g^e_V(\nu e \rightarrow \nu e)$ | −0.025 ± 0.020  | −0.036 ± 0.001 ± 0.001 |
| $\sin^2\theta_W$ | 0.2242 ± 0.0042 ± [0.0047] | 0.2269 ± 0.0003 ± 0.0025 |

Table 2: Current values of LEP and other recent observables. Not all of the LEP observables are independent. The last column are the standard model predictions using $M_Z$ as input and assuming the value and uncertainty in $m_t$ given by the global best fit for $60 \text{GeV} < M_H < 1 \text{TeV}$. 

[100x193] global best fit for 60 GeV < $M_H$ < 1 TeV.
Figure 11: The extracted values of $\sin^2 \hat{\theta}_W(M_Z)$ from various observables as a function of $m_t$. They are all consistent for a top quark mass of around 150 GeV.

Figure 12: $\chi^2$ distributions for various values of the Higgs mass.

dicating that the standard model is correct down to a distance scale of $10^{-16}\text{cm}$ (except possibly for the Higgs sector), as is indicated in Figure [10]. The radiative corrections are essential for the agreement of the various observables, indicating that the basic structure of renormalizable field theory is correct. The weak angle in the $\overline{\text{MS}}$ scheme is now determined very precisely, $\sin^2 \hat{\theta}_W(M_Z) = 0.2328 \pm 0.0007$, where the uncertainty is almost all due to $m_t$. In the on-shell scheme the uncertainty, again dominated by $m_t$, is larger, $\sin^2 \theta_W \equiv 1 - M_W^2/M_Z^2 = 0.2267 \pm 0.0024$. There is a fairly precise prediction $m_t = 150^{+19+15}_{-24-20}$ GeV assuming the standard model. In the minimal supersymmetric extension of the standard model (MSSM) one has the slightly lower value $134^{+23}_{-28} \pm 5$ GeV. The difference is because in the MSSM there is a light scalar which acts like a standard model Higgs but which has a relatively low mass. For most of parameter space the other supersymmetric particles have no significant role on the radiative corrections. The top quark and Higgs mass constraints are strongly correlated, and to a good approximation the predicted value is $m_t = \left(150^{+19}_{-24} + 12.5 \ln \left(\frac{M_H}{300}\right)\right)\text{GeV}$. The origin of the constraints can be seen in Figure [11]. The $\chi^2$ distribu-
Figure 13: 68% and 90% confidence levels on $M_H$ as a function of the top quark mass, assuming that it has been measured directly with a precision of 10 GeV.

The predictions of the fit to all data are shown for various values of the Higgs mass in Figure 12. Although the value predicted for $m_t$ is strongly correlated with the Higgs mass ($M_H$), there will be no independent significant constraint on $M_H$ until after $m_t$ is known directly. The total $\chi^2$ of the fit varies by only 0.6 as the Higgs mass ranges from 60 — 1000 GeV. However, once $m_t$ is known independently with reasonable precision, there may be a marginal constraint on the Higgs mass, at least if $m_t$ is on the low end, as can be seen in Figure 13.

• As can be seen in Figure 4, the more precise coupling constants, especially $\alpha_s$, allow a much more stringent probe of grand unification. It is seen in Figure 14 that the low energy coupling constants do not meet when extrapolated assuming the standard model, but they do meet when extrapolated according to the supersymmetric extension, suggesting the possibility of some form of supersymmetric grand unification at a mass scale of some $10^{16}$ GeV [23]. Instead of just plotting the couplings, one can use $\alpha + \sin^2 \hat{\theta}_W(M_W)$ to predict the strong coupling $\alpha_s$ (Figure 13). One predicts $\alpha_s = 0.125 \pm 0.002$ (input) $\pm 0.01$ (theory). The first uncertainty, from the uncertainties in the input data, is negligible. The second, which is much larger, is due to theoretical uncertainties from threshold corrections at both the low and grand unified scales, and from possible nonrenormalizable operators [24]. This is in excellent agreement with the present experimental value of $\alpha_s = 0.12 \pm 0.01$ (data). However, given the theoretical uncertainties in the prediction, for this application more precise values of $\alpha_s$ would not be useful. One can also apply the more traditional procedure of using $\alpha + \alpha_s$ to predict $\sin^2 \hat{\theta}_W(M_W) = 0.2334 \pm 0.0025$ (input) $\pm 0.003$ (theory). This is in excellent agreement with the experimental value $0.2326 \pm 0.0006$ (data) (this assumes the supersymmetric range for $m_t$). However, given the large uncertainty in the input value of $\alpha_s$, this procedure is less significant than predicting $\alpha_s$. 22
Figure 14: Running coupling constants in ordinary and supersymmetric grand unified theories, from [24].
Figure 15: Predictions of ordinary and supersymmetric grand unified theories for \(\alpha_s\), compared with various experimental determinations, from [24]. The bands are the experimental average 0.12 \(\pm\) 0.01.
Figure 16: Predictions of the ordinary and supersymmetric grand unified theories for $\sin^2 \theta_W$, compared with the experimental value, from [24].
Figure 17: Current regions allowed in $S$ and $T$ from various reactions at 90\% c.l. The standard model predictions are shown as a function of $m_t$.

- One can search for small deviations due to new physics. The precision tests are sensitive to many types of new physics into the TeV range. The model independent analyses of low energy processes have already been discussed. There are now more stringent limits on $\rho_0$ [17]. This could differ from one due to exotic Higgs representations or in models with compositeness, while most superstring theories predict $\rho_0 = 1$. There are also improved limits on the mixings of exotic fermions, which are predicted in most $E_6$ models, with ordinary fermions [13, 25]. The LEP data also allowed much more stringent limits on the mixing of heavy $Z'$ bosons with the ordinary $Z$, though not much improvement on the masses in the absence of mixing [20]. There are stringent limits on new 4-Fermi operators associated, for example, with compositeness or leptoquarks, especially from atomic parity violation [27], and bounds on the $S$, $T$, and $U$ parameters [28], which is a parametrization of types of new physics which only affect the gauge boson self-energies. Currently,

\[
\begin{align*}
T &= +0.05 \pm 0.43 \\
S &= -0.29 \pm 0.46 \\
U &= +0.37 \pm 0.93.
\end{align*}
\]

$T$ is associated with $SU_{2V}$ (vector) breaking, and manifests itself in the strengths $G_F^{NC}/G_F^{CC}$ of the neutral current and charged current amplitudes, and in the $M_W/M_Z$ ratio. $S$ and $U$ are associated with $SU_{2A}$ (axial) breaking, and are manifested by the relation between the low energy couplings and the physical gauge boson masses, $G_F \leftrightarrow M_{W,Z}$. The current constraints on $S$ and $T$ are shown in Figure [17].

- There are various ways to parameterize new physics. The $S$, $T$, $U$ formalism is limited to physics which only affects gauge boson self-energies. An alternate formalism describes all types of new physics [30], but utilizes only a
few of the observables. A general formalism is that of deviation vectors [28], which is a way of describing all possible types of new physics and their effects on all observables. One defines the component

$$D_a = \frac{O^\text{exp}_a - O^\text{SM}_a(M_Z)}{\Delta O_a}$$  \hspace{1cm} (3)$$

of the deviation vector, where $O^\text{exp}_a$ is the experimental value of the $a^{th}$ observable and $O^\text{SM}_a(M_Z)$ is the prediction of the standard model, using $M_Z$ as input. The denominator is the total uncertainty, due to the uncertainties in the experiment, $\Delta M_Z$, the running of $\alpha$ from $Q^2 \sim 0$ up to the Z-pole, $m_t$, and QCD. If the standard model is correct, the components of the deviation vector should be in the approximate range $-1$ to $1$, while if there is a deviation from the standard model the direction (magnitude) of the deviation vector should indicate the type (strength) of the new physics.

The current situation of the most precise observable is shown in Figure 18. In fact, the comparison is too good, suggesting that some of the experiments may have overestimated their systematic uncertainties.
7 The Future

There are many possible future precision experiments.

7.1 Motivations

LEP is the most precise facility for electroweak observables. However, it is sensitive only to the properties of the $Z$ boson, and is blind to many types of new physics which do not directly affect the $Z$. There is a need for other (less precise) observables which are sensitive to such deviations from the standard model as $Z'$ bosons or exotic fermions which do not directly mix with the ordinary particles, new 4-Fermi operators, or leptoquarks. Such experiments would be complementary to direct searches for new particles at high energy colliders and would be useful for excluding possibilities even if no deviations are observed.

7.2 Possible Experiments

The LEP program is still in progress. One can expect improved values of $\Gamma_Z$, $\Gamma_{f\bar{f}}$, $A_{FB}(f)$, and $A_{\text{pol}}(\tau)$. Even at present the precision of some of these observables is better than had ever been anticipated before LEP was built. It is a remarkable accomplishment, and one should complete the program. There may also be precise measurements of the polarization asymmetry, $A_{LR}$, at SLC and LEP. $A_{LR}$ is clean theoretically, most systematic uncertainties cancel, and it is very sensitive to new physics. However, it is perhaps less crucial than had been anticipated because of the success of the other LEP observations.

In addition, we anticipate more precise measurements of $M_W$ to $\sim 100$ MeV at CDF and D0 and at LEP200. We also expect major improvements in the precision of atomic parity violation experiments at Boulder and Paris. In the near future the experiments should improve to the 1% level, with the uncertainty dominated by the theoretical matrix elements. Later, by comparing various isotopes (for which the atomic uncertainties largely cancel) one could obtain a precision of $\ll 1\%$. Atomic parity is very sensitive to some types of deviations, especially new operators associated with compositeness. There is also a possibility of a new deep inelastic $\nu N \rightarrow \nu X$ experiment at Fermilab. This would be at higher energies than before, and many of the theoretical uncertainties would be smaller. Finally, there may be precision experiments at HERA, there are proposals for new generations of $\nu e$ and $\nu p$ scattering at LANL, and there may be $e^{14}N$ experiments at CEBAF, Bates, and possibly SLAC. It is not clear whether the latter will be used more as a test of the standard model, or (assuming the standard model) as a probe of nucleon.
7.3 Implications

Some time ago Luo, Mann, and I became interested in the relative sensitivity of these different proposals, \textit{i.e.}, to what extent would each be sensitive to various types of new physics, which would be more sensitive, and to what extent would they be complementary. We carried out an analysis of many proposed types of new physics and many observables, calculating the expected deviation vectors for some 30 types of new physics for a number of possible observables. A typical example is shown in Figure 19.

The conclusion was that there is no one “best” observable. A number of proposed experiments are important, depending on the type of new physics. A new program of precisions experiments would give an unprecedented test of the structure of renormalizable field theory and would be sensitive to small deviations from the standard model. It is important that as many as possible of these experiments be done to maximize the sensitivity to different types of new physics; to simultaneously determine the parameters of the standard model; to confirm any discrepancies; and to diagnose the origin of discrepancies (\textit{i.e.}, the patterns of deviations for the various experiments are quite different for different types of new physics). To carry out this program it will be important to have a uniform analysis of all of the experiments with consistent definitions of $\sin^2 \theta_W$. At present the situation is confused because different definitions are being used, some of which are effective parameters defined by complicated computer programs. This is adequate as long as one is just treating the LEP data. However, as soon as one tries to compare to other observables or to such theoretical ideas as grand unification the uncertainties in the meaning of these effective parameters become a problem. It would be desirable to use standardized definitions of parameters, such as the $\overline{\text{MS}}$ definition of the weak angle. It is also crucial that careful estimates of systematic uncertainties and correlations be applied to the data.

8 Conclusions

- The weak neutral current plus the $W$ and $Z$ properties are the primary test of electroweak unification.

- These observables have uniquely established the standard model gauge group and fermion representations.

- The standard model is correct to an excellent first approximation down to a distance scale of $10^{-16}$ cm.

- Amongst the results
  - In the $\overline{\text{MS}}$ scheme $\sin^2 \hat{\theta}_W(M_W) = 0.2328 \pm 0.0007$.
  - In the on shell scheme $\sin^2 \theta_W \equiv 1 - M_W^2 / M_Z^2 = 0.2267 \pm 0.0024$. The uncertainties in both cases are largely due to $m_t$. 

29
Figure 19: Sensitivities of a number of types of observables to a particular type of new heavy $Z$ boson. The larger bars represent a higher sensitivity, shown in GeV in the right-hand column. For this particular example, $M_W$, deep inelastic neutrino scattering, atomic parity violation, and various LEP asymmetries are all very sensitive.
One has the predictions $m_t = 150^{+19+15}_{-24-20}$ GeV in the standard model and $134^{+23}_{-25} \pm 5$ GeV in the MSSM.

- Although the values of $M_H$ and $m_t$ are strongly correlated there is no significant $M_H$ constraint until $m_t$ is known directly.

- The observed coupling constants are in remarkable agreement with the predictions of supersymmetric grand unification. This could well be an accident, but on the other hand it may be pointing us toward supersymmetric unification and possibly superstring theories.

- The structure of gauge field theory is confirmed.

- The observables are sensitive to many types of new physics into the TeV range and are an excellent complement to high energy colliders.

- Let us not cut short the program of LEP and other precise measurements; it is unique in the history of particle physics and should not compromised.

- It is important to present all results in terms of well-defined quantities, such as a consistent definition of $\sin^2 \hat{\theta}_W$, to compare the results of different classes of experiments and with the predictions of grand unified theories.

References

[1] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2, 1285 (1970).

[2] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and M. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[3] See, for example, A. Sirlin, *Universality of the Weak Interactions*, to be published in *Precision Tests of the Standard Electroweak Model* (World, Singapore, 1993), ed. P. Langacker.

[4] For a review and analysis, see J. E. Kim, P. Langacker, M. Levine, and H. H. Williams, Rev. Mod. Phys. 53, 211 (1981).

[5] SLAC: C. Y. Prescott et al., Phys. Lett. B4B, 524 (1979).

[6] J. D. Bjorken, *Proc. of the SLAC Summer Inst. on Particle Physics*, ed. M. Zipf, SLAC-195; P. Q. Hung and J. J. Sakurai, Phys. Lett. B63, 295 (1976); B69, 323 (1972); B72, 208 (1977); L. M. Sehgal, Phys. Lett. B71, 91 (1977).

[7] For a review, see P. Langacker, Phys. Rep. C72, 185 (1981).
[8] S. Dimopoulos, S. Raby and F. Wilczek, Phys. Rev. D24, 1681 (1981); W. J. Marciano and G. Senjanović, Phys. Rev. D25, 3092 (1982); L. E. Ibáñez and G. G. Ross, Phys. Lett. B105, 439 (1982); M. B. Einhorn and D. R. T. Jones, Nucl. Phys. B196, 475 (1982).

[9] For a review, see W. Marciano, *Radiative Corrections to Neutral Current Processes*, to be published in *Precision Tests of the Standard Electroweak Model*.

[10] C. H. Llewellyn-Smith, Nucl. Phys. B228, 205 (1983).

[11] U. Amaldi, A. Böhm, L. S. Durkin, P. Langacker, A. K. Mann, W. J. Marciano, A. Sirlin, and H. H. Williams, Phys. Rev. D36, 1385 (1987). A similar analysis was done by G. Costa, J. Ellis, G. L. Fogli, D. V. Nanopoulos, and F. Zwirner, Nucl. Phys. B297, 244 (1988). Deep inelastic scattering was also considered by G. L. Fogli and D. Haidt, Z. Phys. C40, 379 (1988).

[12] L. S. Durkin and P. Langacker, Phys. Lett. 166B, 436 (1986).

[13] P. Langacker and D. London, Phys. Rev. D38, 886 (1988).

[14] CHARM II: D. Geiregat *et al.*, Phys. Lett. B259, 499 (1991); S. Cocco, *XXVIIth Rencontres de Moriond*, March 1992.

[15] R. C. Allen *et al.*, Phys. Rev. D47, 11 (1993).

[16] P. Langacker, Comm. Nucl. Part. Sci. 19, 1 (1989).

[17] P. Langacker and M. Luo, Phys. Rev. D44, 817 (1991).

[18] The LEP Collaborations, Phys. Lett. B276, 247 (1992). D. Schaile, to be published in *Precision Tests of the Standard Electroweak Model*.

[19] SLD: K. Abe *et al.*, Phys. Rev. Lett. 70, 2515 (1993).

[20] CDF: F. Abe *et al.*, Phys. Rev. Lett. 65, 2243 (1990).

[21] UA2: J. Alitti *et al.*, Phys. Lett. B276, 354 (1992).

[22] Cesium: M. C. Noecker *et al.*, Phys. Rev. Lett. 61, 310 (1988).

[23] P. Langacker and M. Luo, Phys. Rev. D44, 817 (1991); U. Amaldi, W. de Boer and H. Fürstenau, Phys. Lett. B260, 447 (1991). J. Ellis, S. Kelley and D. V. Nanopoulos, Phys. Lett. B249, 441 (1990). F. Anselmo, L. Cifarelli, A. Peterman, and A. Zichichi, Nuo. Cim. 104A, 1817 (1991).

[24] P. Langacker and N. Polonsky, Phys. Rev. D47, 4028 (1993).
[25] E. Nardi, E. Roulet, and D. Tommasini, Nucl. Phys. B386, 239 (1992), Phys. Rev. D46, 3040 (1992).

[26] For a recent review, see P. Langacker, *Tests of the Standard Model and Searches for New Physics*, to be published in *Precision Tests of the Standard Electroweak Model*.

[27] P. Langacker, Phys. Lett. B256, 277 (1991); see also [28].

[28] P. Langacker, M. Luo, and A. Mann, Rev. Mod. Phys. 64, 87 (1992).

[29] For reviews, see M. Peskin and T. Takeuchi, Phys. Rev. D46, 381 (1992); P. Langacker, *Review of Particle Properties*, Phys. Rev. D45, VII-159 (1992); and [28].

[30] G. Altarelli, R. Barbieri, and S. Jadach, Nucl. Phys. B369, 3 (1992).