Electroweak Physics

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Abstract. The results of high precision weak neutral current (WNC), Z-pole, and high energy collider electroweak experiments have been the primary prediction and test of electroweak unification. The electroweak program is briefly reviewed from a historical perspective. Current changes, anomalies, and things to watch are summarized, and the implications for the standard model and beyond discussed.

THE Z, THE W, AND THE WEAK NEUTRAL CURRENT

The weak neutral current was a critical prediction of the electroweak standard model (SM) [1, 2]. Following its discovery in 1973 by the Gargamelle and HPW experiments, there were generations of ever more precise WNC experiments, typically at the few % level. These included pure weak $\nu N$ and $\nu e$ scattering processes, and weak-electromagnetic interference processes such as polarized $e^\uparrow D$ or $\mu N$, $e^+ e^- \rightarrow$ (hadron or charged lepton) cross sections and asymmetries below the Z pole, and parity-violating effects in heavy atoms (APV). There were also early direct observations of the W and Z by UA1 and UA2. The early 1990’s witnessed the very precise Z-pole experiments at LEP and the SLC, in which the lineshape, decay modes, and various asymmetries were measured at the 0.1% level. The subsequent LEP 2 program at higher energies measured $M_W$, searched for the Higgs and other new particles, and constrained anomalous gauge self-interactions. Parallel efforts at the Tevatron by CDF and DØ led to the direct discovery of the $t$ and measurements of $m_t$ and $M_W$, while a fourth generation of weak neutral current experiments continued to search for new physics to which the (more precise) Z-pole experiments were blind. The program was supported by theoretical efforts in the calculation of QCD and electroweak radiative corrections; the expectations for observables in the standard model, large classes of extensions, and alternative models; and global analyses of the data.

The precision program has established that the standard model (SM) is correct and unique to first approximation, establishing the gauge principle as well as the SM gauge group and representations; shown that the SM is correct at loop level, confirming the basic principles of renormalizable gauge theory and allowing the successful prediction or constraint on $m_t$, $\alpha_s$, and the Higgs mass $M_H$; severely constrained new physics at the TeV scale, with the ideas of unification strongly favored over TeV-scale compositeness; and yielded precise values for the gauge couplings, consistent with (supersymmetric) gauge unification.
RESULTS BEFORE THE LEP/SLD ERA

Even before the beginning of the Z-pole experiments at LEP and SLC in 1989, the precision program had established [2]-[5]:

- Global analyses of all data carried more information than the analysis of individual experiments, but care has to be taken with systematic and theoretical uncertainties.
- The SM is correct to first approximation. The four-fermion operators for $\nu q$, $\nu e$, and $eq$ were uniquely determined, in agreement with the standard model, in model (i.e., gauge group) independent analyses. The $W$ and $Z$ masses agreed with the expectations of the $SU(2) \times U(1)$ gauge group and canonical Higgs mechanism, eliminating contrived alternative models with the same four-fermi interactions as the standard model.
- QCD evolved structure functions and electroweak radiative corrections were necessary for the agreement of theory and experiment.
- The weak mixing angle (in the on-shell renormalization scheme) was determined to be $\sin^2 \theta_W = 0.230 \pm 0.007$; consistency of the various observations, including radiative corrections, required $m_t < 200$ GeV.
- Theoretical uncertainties, especially in the $c$ threshold in deep inelastic weak charge current (WCC) scattering, dominated.
- The combination of WNC and WCC data uniquely determined the $SU(2)$ representations of all of the known fermions, i.e., $\nu_e$ and $\nu_\mu$, as well as the $L$ and $R$ components of the $e$, $\mu$, $\tau$, $d$, $s$, $b$, $u$, and $c$ [6]. In particular, the left-handed $b$ and $\tau$ were the lower components of $SU(2)$ doublets, implying unambiguously that the $t$ quark and $\nu_\tau$ had to exist. This was independent of theoretical arguments based on anomaly cancellation (which could have been evaded in alternative models involving a vector-like third family), and of constraints on $m_t$ from electroweak loops.
- The electroweak gauge couplings were well-determined, allowing a detailed comparison with the gauge unification predictions of the simplest grand unified theories (GUT). Ordinary $SU(5)$ was excluded (consistent with the non-observation of proton decay), but the supersymmetric extension was allowed, “perhaps even the first harbinger of supersymmetry” [4].
- There were stringent limits on new physics at the TeV scale, including additional $Z'$ bosons, exotic fermions (for which both WNC and WCC constraints were crucial), exotic Higgs representations, leptoquarks, and new four-fermion operators.

THE LEP/SLC ERA

The LEP/SLC era greatly improved the precision of the electroweak program. It allowed the differentiation between non-decoupling extensions to the SM (such as most forms of dynamical symmetry breaking and other types of TeV-scale compositeness), which typically predicted several % deviations, and decoupling extensions (such as most of the parameter space for supersymmetry), for which the deviations are typically 0.1%.
The first phase of the LEP/SLC program involved running at the $Z$ pole, $e^+e^- \rightarrow Z \rightarrow \ell^+\ell^-$, $q\bar{q}$, and $\nu\bar{\nu}$. During the period 1989-1995 the four LEP experiments ALEPH, DELPHI, L3, and OPAL at CERN observed $\sim 2 \times 10^7 Z$'s. The SLD experiment at the SLC at SLAC observed some $5 \times 10^5$ events. Despite the much lower statistics, the SLC had the considerable advantage of a highly polarized $e^-$ beam, with $P_{e^-} \sim 75\%$. There were quite a few $Z$ pole observables, including:

- The lineshape: $M_Z, \Gamma_Z$, and the peak cross section $\sigma$.
- The branching ratios for $e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, c\bar{c}, b\bar{b}$, and $s\bar{s}$. One could also determine the invisible width, $\Gamma$(inv), from which one can derive the number $N_V = 2.986 \pm 0.007$ of active (weak doublet) neutrinos with $m_{\nu} < M_Z/2$, i.e., there are only 3 conventional families with light neutrinos. $\Gamma$(inv) also constrains other invisible particles, such as light sneutrinos and the light majorons associated with some models of neutrino mass.
- A number of asymmetries, including forward-backward (FB) asymmetries; the $\tau$ polarization, $P_\tau$; the polarization asymmetry $A_{LR}$ associated with $P_\tau$; and mixed polarization-FB asymmetries.

The expressions for the observables are summarized in [1, 2], and the experimental values and SM predictions in Table 1. The precision of the $Z$ mass determination was extraordinary for a high energy experiment. These combinations of observables could be used to isolate many $Z$-fermion couplings, verify lepton family universality, determine $\sin^2 \theta_W$ in numerous ways, and determine or constrain $m_t$, $\alpha_s$, and $M_H$. LEP and SLC simultaneously carried out other programs, most notably studies and tests of QCD, and heavy quark physics.

LEP 2 ran from 1995-2000, with energies gradually increasing from $\sim 140$ to $\sim 209$ GeV. The principal electroweak results were precise measurements of the $W$ mass, as well as its width and branching ratios (these were measured independently at the Tevatron); a measurement of $e^+e^-\rightarrow W^+W^-, ZZ,$ and single $W$, as a function of center of mass (CM) energy, which tests the cancellations between diagrams that is characteristic of a renormalizable gauge field theory, or, equivalently, probes the triple gauge vertices; limits on anomalous quartic gauge vertices; measurements of various cross sections and asymmetries for $e^+e^-\rightarrow f\bar{f}$ for $f = \mu^-, \tau-, q,b$ and $c$, in reasonable agreement with SM predictions; a stringent lower limit of 114.4 GeV on the Higgs mass, and even hints of an observation at $\sim 116$ GeV; and searches for supersymmetric or other exotic particles.

In parallel with the LEP/SLC program, there were precise ($< 1\%$) measurements of atomic parity violation (APV) in cesium at Boulder, along with the atomic calculations and related measurements needed for the interpretation; precise new measurements of deep inelastic scattering by the NuTeV collaboration at Fermilab, with a sign-selected beam which allowed them to minimize the effects of the $c$ threshold and reduce uncertainties to around 1$\%$; and few measurements of $\bar{\nu}_\mu e$ by CHARM II at CERN. Although the precision of these WNC processes was lower than the $Z$ pole measurements, they are still of considerable importance; the $Z$ pole experiments are blind to types of new physics that do not directly affect the $Z$, such as a heavy $Z'$ if there is no $Z - Z'$ mixing, while the WNC experiments are often very sensitive. During the same period there were important electroweak results from CDF and $D\phi$ at the Tevatron, most notably a
TABLE 1. Principal Z-pole observables, their experimental values, theoretical predictions using the SM parameters from the global best fit as of 1/03 (updated from [2]), and pull (difference from the prediction divided by the uncertainty). See [1] for definitions of the quantities. \( \Gamma(\text{had}), \Gamma(\text{inv}), \) and \( \Gamma(\ell^+\ell^-) \) are not independent.

| Quantity     | Group(s) | Value        | Standard Model | pull  |
|--------------|----------|--------------|----------------|-------|
| \( M_Z \) [GeV] | LEP      | 91.1876 ± 0.0021 | 91.1874 ± 0.0021 | 0.1   |
| \( \Gamma_Z \) [GeV] | LEP      | 2.4952 ± 0.0023  | 2.4972 ± 0.0011  | −0.9  |
| \( \Gamma(\text{had}) \) [GeV] | LEP      | 1.7444 ± 0.0020  | 1.7436 ± 0.0011  | −       |
| \( \Gamma(\text{inv}) \) [MeV] | LEP      | 499.0 ± 1.5     | 501.74 ± 0.15     | −       |
| \( \Gamma(\ell^+\ell^-) \) [MeV] | LEP      | 83.984 ± 0.086   | 84.015 ± 0.027    | −       |
| \( \sigma_{\text{had}} \) [nb] | LEP      | 41.541 ± 0.037   | 41.470 ± 0.010    | 1.9   |
| \( R_\ell \) | LEP      | 20.804 ± 0.050   | 20.753 ± 0.012    | 1.0   |
| \( R_\mu \) | LEP      | 20.785 ± 0.033   | 20.753 ± 0.012    | 1.0   |
| \( R_\tau \) | LEP      | 20.764 ± 0.045   | 20.799 ± 0.012    | −0.8  |
| \( A_{FB}(e) \) | LEP      | 0.0145 ± 0.0025  | 0.01639 ± 0.00026 | −0.8  |
| \( A_{FB}(\mu) \) | LEP      | 0.0169 ± 0.0013  | 0.4   |
| \( A_{FB}(\tau) \) | LEP      | 0.0188 ± 0.0017  | 1.4   |
| \( R_{b} \) | LEP/SLD  | 0.21664 ± 0.00065 | 0.21572 ± 0.00015 | 1.1   |
| \( R_{c} \) | LEP/SLD  | 0.1718 ± 0.0031  | 0.17231 ± 0.00006 | −0.2  |
| \( R_{s,d}/R_{(d+u+s)} \) | OPAL    | 0.371 ± 0.023    | 0.35918 ± 0.00004 | 0.5   |
| \( A_{FB}(b) \) | LEP      | 0.0995 ± 0.0017  | 0.1036 ± 0.0008   | −2.4  |
| \( A_{FB}(c) \) | LEP      | 0.0713 ± 0.0036  | 0.0741 ± 0.0007   | −0.8  |
| \( A_{FB}(s) \) | DELPHI/OPAL | 0.0976 ± 0.0114 | 0.1037 ± 0.0008   | −0.5  |
| \( A_{b} \) | SLD      | 0.922 ± 0.020   | 0.93476 ± 0.00012 | −0.6  |
| \( A_{t} \) | SLD      | 0.670 ± 0.026   | 0.6681 ± 0.0005   | 0.1   |
| \( A_{s} \) | SLD      | 0.895 ± 0.091   | 0.93571 ± 0.00010 | −0.4  |
| \( A_{LR} \) (hadrons) | SLD | 0.15138 ± 0.00216 | 0.1478 ± 0.0012    | 1.7   |
| \( A_{LR} \) (leptons) | SLD  | 0.1544 ± 0.0060  | 1.1   |
| \( A_{\mu} \) | SLD      | 0.142 ± 0.015   | −0.4  |
| \( A_{\tau} \) | SLD      | 0.136 ± 0.015   | −0.8  |
| \( A_{\mu}(Q_{LR}) \) | SLD | 0.162 ± 0.043   | 0.3   |
| \( A_{\tau}(Q_{LR}) \) | LEP    | 0.1439 ± 0.0043  | −0.9  |
| \( A_{\tau}(R_{\tau}) \) | LEP    | 0.1498 ± 0.0048  | 0.4   |
| \( Q_{FB} \) | LEP      | 0.0403 ± 0.0026  | 0.0424 ± 0.0003    | −0.8  |

precise value for \( M_W \), competitive with and complementary to the LEP 2 value; a direct measure of \( m_t \), and direct searches for \( Z' \), \( W' \), exotic fermions, and supersymmetric particles. Many of these non-\( Z \)-pole results are summarized in Table 2.

The effort required the calculation of the needed electromagnetic, electroweak, QCD, and mixed radiative corrections to the predictions of the SM. Careful consideration of the competing definitions of the renormalized \( \sin^2 \theta_W \) was needed. The principal theoretical uncertainty is the hadronic contribution \( \Delta \alpha_{\text{had}}^{(5)}(M_Z) \) to the running of \( \alpha \) from its precisely known value at low energies to the \( Z \)-pole, where it is needed to compare the \( Z \) mass with the asymmetries and other observables. The radiative corrections, renormalization schemes, and running of \( \alpha \) are further discussed in [1, 2]. The LEP Electroweak Working Group (LEPEWWG) [7] combined the results of the four LEP experiments, and also those of SLD and some WNC and Tevatron results, taking proper account of common systematic and theoretical uncertainties. Much theoretical effort also

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TABLE 2. Non-Z-pole observables, 1/03. The SM values are updated from [2].

| Quantity | Group(s) | Value       | Standard Model | pull |
|----------|----------|-------------|----------------|------|
| $m_t$ [GeV] | Tevatron | 174.3 ± 5.1 | 174.4 ± 4.4 | 0.0  |
| $M_W$ [GeV] | LEP      | 80.447 ± 0.042 | 80.391 ± 0.018 | 1.3  |
| $M_W$ [GeV] | Tevatron /UA2 | 80.454 ± 0.059 |             | 1.1  |
| $g_\nu^e$ | NuTeV    | 0.30005 ± 0.00137 | 0.30396 ± 0.00023 | −2.9 |
| $g_\nu^\tau$ | NuTeV | 0.03076 ± 0.00110 | 0.03005 ± 0.00004 | 0.6  |
| $R^\nu$ | CCFR     | 0.5820 ± 0.0027 ± 0.0031 | 0.5833 ± 0.0004 | −0.3 |
| $R^\nu$ | CDHS     | 0.3096 ± 0.0033 ± 0.0028 | 0.3092 ± 0.0002 | 0.1  |
| $R^\nu$ | CHARM   | 0.3021 ± 0.0031 ± 0.0026 |             | −1.7 |
| $R^\nu$ | CDHS     | 0.384 ± 0.016 ± 0.007 | 0.3862 ± 0.0002 | −0.1 |
| $R^\nu$ | CHARM   | 0.403 ± 0.014 ± 0.007 |             | 1.0  |
| $R^\nu$ | CDHS 1979 | 0.365 ± 0.015 ± 0.007 | 0.3816 ± 0.0002 | −1.0 |
| $g_\nu^{V_e}$ | CHARMLII | 0.035 ± 0.017 | −0.0398 ± 0.0003 | —    |
| $g_\nu^{V_\tau}$ | all | −0.041 ± 0.015 |             | −0.1 |
| $g_\nu^{A_1}$ | CHARMLII | −0.503 ± 0.017 | −0.5065 ± 0.0001 | —    |
| $g_\nu^{A_2}$ | all | −0.507 ± 0.014 |             | 0.0  |
| $Q_W (\text{Cs})$ | Boulder | −72.69 ± 0.44 | −73.10 ± 0.04 | 0.8  |
| $Q_W (\text{Ti})$ | Oxford/Seattle | −116.6 ± 3.7 | −116.7 ± 0.1 | 0.0  |
| $10^3 \frac{(\beta - \alpha)}{\beta}$ | BaBar/Belle/CLEO | 3.48±0.65 | 3.20±0.09 | 0.5  |
| $\tau_\tau \text{[fs]}$ | direct/$\beta_\ell / \beta_\mu$ | 290.96 ± 0.59 ± 5.66 | 291.90 ± 1.81 | −0.4 |
| $10^4 \Delta \alpha^{(3)}_{\text{had}}$ | $e^+e^-\tau$ decays | 56.53 ± 0.83 ± 0.64 | 57.52 ± 1.31 | −0.9 |
| $10^9 (a_\mu - \frac{g}{\pi})$ | BNL/CERN | 4510.64 ± 0.79 ± 0.51 | 4508.30 ± 0.33 | 2.5  |

went into the development, testing, and comparison of radiative corrections packages, and into the study of how various classes of new physics would modify the observables, and how they could most efficiently be parametrized.

**NEW INPUTS, ANOMALIES, THINGS TO WATCH**

The results in Tables 1 and 2 are from 1/03, while the fit results to be presented in the next Section are from June 2002, updated from [2]. Jens Erler and I are currently performing a new analysis for the next edition of the *Review Of Particle Physics*; it is useful to list here some of the things that have or will change or to watch for.

- As of 3/03, the LEP 2 value for the $W$ mass, 80.412(42) GeV, is smaller than the previous value of 80.447(42) GeV (used in Table 2) due to a revised ALEPH analysis [7]. This is closer to the SM best fit prediction of 80.391(18) GeV and will lead to a small increase in the predicted $M_H$. The Tevatron (CDF, DØ) Run I/UA2 value of 80.454(59) GeV is also slightly high. A new Run II value is expected.
- The direct lower limit on the SM Higgs mass from LEP 2 is $M_H > 114.4$ GeV (95% cl). The hints for events around 116 GeV were weakened in the final analysis.
- A more precise $m_t$ from the Tevatron Run II is awaited. The preliminary CDF and DØ values still have large uncertainties [8]. A new preliminary DØ analysis of their
There is a new estimate of $\alpha_s$ from the $\tau$ lifetime [9], which is quite precise though theory-error dominated, yielding $\alpha_s(M_\tau) = 0.356^{+0.027}_{-0.021}$, corresponding to $\alpha_s(M_Z) = 0.1221^{+0.0026}_{-0.0023}$.

$A_{FB}(b)$, the forward-backward asymmetry into $b$ quarks, has the value 0.0995(17), 2.4$\sigma$ below the standard model global fit value of 0.1036(8). However, the SLD value for the related quantity $A_b = 0.922(20)$ is only 0.6$\sigma$ below the expected 0.9348(1), and the hadronic branching fraction $R_b = 0.2166(7)$, which at one time appeared anomalous, is now only 1.1$\sigma$ above the expectation 0.2157(2). If not just a statistical fluctuation or systematic problem, $A_{FB}(b)$ could be a hint of new physics. However, any such effect should not contribute too much to $R_b$. The deviation is only around 5%, but if the new physics involved a radiative correction to the coefficient $\kappa$ of $\sin^2 \theta_W$, the change would have to be around 25%. Hence, the new physics would most likely be at the tree level, mainly increasing the magnitude of the right-handed coupling to the $b$. This could be due to a heavy $Z'$ boson with non-universal couplings to the third family [10, 11]; or to the mixing of the $b_R$ with exotic quarks [2, 12], such as with an $SU(2)$ doublet involving a heavy $B_R$ quark and a charge $-4/3$ partner [12]. There is a strong correlation between $A_{FB}(b)$ and the predicted Higgs mass $M_H$ in the global fits. It has been emphasized [13] that if one eliminated $A_{FB}(b)$ from the fit (e.g., because it is affected by new physics) then the $M_H$ prediction would be lower, with the central value well below the lower limit from the direct searches at LEP 2. One resolution, assuming $A_{FB}(b)$ is due to an experimental problem or fluctuation, is to invoke a supersymmetric extension of the standard model with light sneutrinos, sleptons, and possibly gauginos [14], which modify the radiative corrections and allow an acceptable $M_H$.

The NuTeV collaboration at Fermilab [15] have reported the results of their deep inelastic measurements of $\frac{-\nu_{\mu} N \rightarrow -\nu_{\mu} X}{\nu_{\mu} N \rightarrow -\mu^+ X}$. They greatly reduce the uncertainty in the charm quark threshold in the charged current denominator by taking appropriate combinations of $\nu_{\mu}$ and $\bar{\nu}_{\mu}$. They find a value for the on-shell weak angle $s_W^2$ of 0.2277(16), which is 3.0$\sigma$ above the global fit value of 0.2228(4). The corresponding values for the left and right handed neutral current couplings [2] are $g_L^2 = 0.3001(14)$ and $g_R^2 = 0.0308(11)$, which are respectively 2.9$\sigma$ below and 0.7$\sigma$ above the expected 0.3040(2) and 0.0300(0). Possible standard model explanations include an unexpectedly large violation of isospin in the quark sea [15]; an asymmetric strange sea [16], though NuTeV’s data seems to favor the wrong sign for this effect; nuclear shadowing effects [17]; or next to leading order QCD effects [16].

More exotic interpretations could include a heavy $Z'$ boson [10, 16], although the standard GUT-type $Z'$s do not significantly improve the fits, suggesting the need for a $Z'$ with “designer” couplings. Mixing of the $\nu_{\mu}$ with a heavy neutrino could account for the effect [18, 19], and also for the slightly low value for the number of light neutrinos $N_{\nu} = 2.986(7)$ from the $Z$ line shape when $N_{\nu}$ is allowed to
deviate from 3 (this shows up as a slightly high hadronic peak cross section in the standard model fit with $N = 3$) [2, 10]. This mixing would also affect muon decay, leading to an apparent Fermi constant smaller than the true value. This would be problematic for the other Z-pole observables, but could be compensated by a large negative $T$ parameter [19]. However, such mixings would also lead to a lower value for $|V_{ud}|$, significantly aggravating the universality problem discussed below.

• The Brookhaven $g\mu - 2$ experiment has reported a precise new value [20] using positive muons, leading to a new world average $a_{\mu} = 11659203(8) \times 10^{-10}$. Improvements in the statistical error from negative muon runs are anticipated. Using the theoretical value quoted by the experimenters for the hadronic vacuum polarization contribution $a_{\mu}^{\text{had}}$, there was a small discrepancy, with $a_{\mu}(\text{exp}) - a_{\mu}(\text{SM}) = (26 \pm 11) \times 10^{-10}$, a 2.6σ effect. The value and uncertainty in $a_{\mu}^{\text{had}}$ are still controversial: subsequent analyses based on $e^+e^-$ data [21, 22] found a 3σ discrepancy, while an analysis using $\tau$ decay data [21] found a smaller 1σ effect. Recently the CDM-2 collaboration found a mistake in their theoretical code for the $e^+e^-\rightarrow e^+e^-$ cross section, used to determine the luminosity in the hadronic cross section [23]. This should lower the discrepancy from $e^+e^-$ data to around 2σ, closer to the $\tau$ value. New data from KLOE is anticipated.

Because of the confused situation with the vacuum polarization, it is hard to know how seriously to take the discrepancy. Nevertheless, $a_{\mu}$ is more sensitive than the electron moment to most types of new physics, so it is important. One obvious candidate for a new physics explanation would be supersymmetry [24], with relatively low masses for the relevant sparticles and high $\tan\beta$ (roughly, one requires an effective mass scale of $\tilde{m} \sim 55\text{ GeV} \sqrt{\tan\beta}$). There is a correlation between the theoretical uncertainty in the vacuum polarization and in the hadronic contribution to the running of $\alpha$ up to the Z-pole [25], leading to a slight reduction in the predicted Higgs mass when $a_{\mu}$ is included in the global fit assuming the standard model.

• $\Delta\alpha^{(5)}(M_Z)$, the hadronic contribution to the running of $\alpha$ up to the Z-pole, introduces the largest theoretical uncertainty into the precision program, in particular to the relation between $M_Z$ and the MS weak angle $s^2_Z$ (extracted mainly from the asymmetries). The uncertainty is closely related to that in $a_{\mu}^{\text{had}}$. There has been much recent progress using improved QCD calculations for the high energy part and more precise $e^+e^-$ data from BES and elsewhere for the low energy part.

• A few years ago there was an apparent 2.3σ discrepancy between the measured value of the effective (parity-violating) weak charge $Q_W(Cs)$ measured in cesium [26], and the expected value. Cesium has a single electron outside a tightly bound core, so the atomic matrix elements could be reliably calculated, leading (it was thought) to a combined theoretical and experimental uncertainty of around 0.6%. However, it turns out that there are surprisingly large ($O(1\%)$) radiative corrections, including Breit (magnetic) interactions, vacuum polarization, vertex, and

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1 There are also uncertainties in the smaller hadronic light by light diagram. An unfortunate sign error increased the apparent discrepancy with experiment at an earlier stage, but this has now been corrected.
self-energy corrections [27, 28]. After a somewhat confusing period, the situation has apparently stabilized, with the current value [28], $Q_W(Cs) = -72.84(46)$, in excellent agreement with the SM expectation, $-73.10(4)$. (An earlier $-72.69(44)$ is listed in Table 1.)

- The unitarity of the CKM matrix can be partially tested by the universality prediction that $\Delta \equiv 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2$ should vanish. In particular $|V_{ud}|$ can be determined by the ratio of $G^V_\beta / G_\mu$, where $G^V_\beta$ and $G_\mu$ are respectively the vector coupling in $\beta$ decay and the $\mu$ decay constant. The most precise determination of $|V_{ud}|$ is from superallowed $0^+ \rightarrow 0^+$ transitions, currently yielding $|V_{ud}| = 0.9740(5)$ [29]. Combining with the PDG values for $|V_{us}|$ from kaon and hyperon decays and $|V_{ub}|$ from $b$ decays, this yields a 2.3$\sigma$ discrepancy $\Delta = 0.0032(14)$, suggesting either the presence of unaccounted-for new physics, or, possibly, effects from higher order isospin violation such as nuclear overlap corrections. However, the latter have been carefully studied, so the effect may be real. This problem has been around for some time, but until recently less precise determinations from neutron decay were consistent with universality. Recently, a more precise measurement of the neutron decay asymmetry has been made by the PERKEO-II group at ILL [30]. When combined with the accurately known neutron lifetime, this allowed the new determination $|V_{ud}| = 0.9713(13)$, implying $\Delta = 0.0083(28)$, i.e., a 3$\sigma$ violation of unitarity. Note, however, that this value is only marginally consistent with the value obtained from superallowed transitions.

Mixing of the $\nu_\mu$ with a heavy neutrino, suggested as a solution of the NuTeV anomaly, would mean that $G_\mu$ is larger than the apparent value and would aggravate this discrepancy. ($\nu_e$ mixing would affect $G^V_\beta$ and $G_\mu$ in the same way and have no effect.) However, a very small mixing of the $W$ boson with a heavy $W'$ coupling to right handed currents, as in left-right symmetric models, could easily account for the discrepancy for the appropriate sign for the mixing [31], especially if the right-handed neutrinos are Majorana and too heavy to be produced in the decays.

The situation has recently become more complicated, by the suggestion that the culprit may be in the long accepted value of $|V_{us}|$. The BNL E865 experiment has recently performed a high statistics measurement of the $K^+_{e3}$ branching ratio [32], obtaining a result 2.3$\sigma$ higher than the old measurements. This would be sufficient to account for the entire discrepancy, but must be confirmed by new analyses and measurements from KLOE, CMD-2 and NA48.

- The LEP and SLC Z-pole experiments are the most precise tests of the standard electroweak theory, but they are insensitive to any new physics that doesn’t affect the Z or its couplings. Non-Z-pole experiments are therefore extremely important, especially given the possible NuTeV anomaly. In the near future we can expect new results in polarized Møller scattering from SLAC [33], and in the QWEAK polarized electron experiment at Jefferson Lab [34].

- Although the Z-pole program has ended for the time being, there are prospects for future programs using the Giga-Z option at a linear collider, which might yield a factor $10^2$ more events. This would enormously improve the sensitivity [35], but would also require a large theoretical effort to improve the radiative correction calculations.
FIT RESULTS (06/02)

As of June, 2002, the result of the global fit was

\[
\begin{align*}
M_H &= 86^{+49}_{-32} \text{ GeV}, \\
mt &= 174.2 \pm 4.4 \text{ GeV}, \\
\alpha_s &= 0.1210 \pm 0.0018, \\
\hat{\alpha}(M_Z)^{-1} &= 127.922 \pm 0.020 \\
\hat{s}_Z^2 &= 0.23110 \pm 0.00015, \\
\chi^2 / \text{d.o.f.} &= 49.0/40 (15\%) 
\end{align*}
\]

The precision data alone yield \( m_t = 174.0^{+9.9}_{-7.4} \text{ GeV} \) from loop corrections, in impressive agreement with the direct Tevatron value 174.3 \pm 5.1. The result \( \alpha_s = 0.1210 \pm 0.0018 \) for the strong coupling is somewhat above the previous world average \( \alpha_s = 0.1172(20) \), which includes other determinations, most of which are dominated by theoretical uncertainties [36]. This is due in part to the inclusion of the new \( \tau \) lifetime result [9]. (Without it, one would obtain \( \alpha_s = 0.1200 \pm 0.0028 \).) The Z-pole value is insensitive to oblique (propagator) new physics, but is very sensitive to non-universal new physics, such as those which affect the \( Z\bar{b}b \) vertex.

The prediction for the Higgs mass from indirect data, \( M_H = 86^{+49}_{-32} \text{ GeV} \), should be compared with the direct LEP 2 limit \( M_H > 114.4(95\%) \) GeV. The theoretical range in the standard model is \( 115 \text{ GeV} \lesssim M_H \lesssim 750 \text{ GeV} \), where the lower (upper) bound is from vacuum stability (triviality). In the MSSM, one has \( M_H \lesssim 130 \text{ GeV} \), while \( M_H \) can be as high as 150 GeV in generalizations. Including the direct LEP 2 exclusion results, one finds \( M_H < 215 \text{ GeV} \) at 95\%. \( M_H \) enters the expressions for the radiative corrections logarithmically. It is fairly robust to many types of new physics, with some exceptions. In particular, a much larger \( M_H \) would be allowed for negative values for the \( S \) parameter or positive values for \( T \). The predicted value would decrease if new physics accounted for the value of \( A_{FB}(b) \) [13].

BEYOND THE STANDARD MODEL

The \( \rho_0 \) or \( S \), \( T \), and \( U \) parameters describe the tree level effects of Higgs triplets, or the loop effects on the \( W \) and \( Z \) propagators due to such new physics as nondegenerate fermions or scalars, or chiral families (expected, for example, in extended technicolor). The current values are:

\[
\begin{align*}
S &= -0.14 \pm 0.10 (-0.08) \\
T &= -0.15 \pm 0.12 (+0.09) \\
U &= 0.32 \pm 0.12 (+0.01) (2.6\sigma)
\end{align*}
\]

for \( M_H = 115.6 (300) \text{ GeV} \), where these represent the effects of new physics only (the \( m_t \) and \( M_H \) effects are treated separately). Similarly, \( \rho_0 \sim 1 + \alpha T = 0.9997^{+0.0011}_{-0.0008} \) for
\[ M_H = 73^{+106}_{-34} \text{ GeV} \] and \[ S = U = 0. \] If one constrains \[ T = U = 0, \] then \[ S = 0.10^{+0.12}_{-0.30} \]. There is a strong negative \( S - M_H \) correlation, so that the Higgs mass constraint is relaxed to \( M_H < 570 \text{ GeV} \) at 95%. For \( M_H \) fixed at 115.6 GeV, one finds \( S = -0.040(62), \) which implies that the number of ordinary plus degenerate heavy families is constrained to be \( N_{\text{fam}} = 2.81 \pm 0.29. \) This is complementary to the lineshape constraint, \( N_{\nu} = 2.986 \pm 0.007, \) which only applies to neutrinos less massive than \( M_Z/2. \) One can also restrict additional nondegenerate families by allowing both \( S \) and \( T \) to be nonzero, yielding \( N_{\text{fam}} = 2.79 \pm 0.43 \) for \( T = -0.01 \pm 0.11. \)

In the decoupling limit of supersymmetry, in which the sparticles are heavier than \( \gtrsim 200 - 300 \text{ GeV}, \) there is little effect on the precision observables, other than that there is necessarily a light SM-like Higgs, consistent with the data. There is little improvement on the SM fit, and in fact one can somewhat constrain the supersymmetry breaking parameters [37].

Heavy \( Z' \) bosons are predicted by many grand unified and string theories [2]. Limits on the \( Z' \) mass are model dependent, but are typically around \( M_{Z'} > 500 - 800 \text{ GeV} \) from indirect constraints from WNC and LEP 2 data, with comparable limits from direct searches at the Tevatron. \( Z \)-pole data severely constrains the \( Z - Z' \) mixing, typically \( |\theta_{Z-Z'}| < \text{few} \times 10^{-3}. \) A heavy \( Z' \) would have many other theoretical and experimental implications [38].

Precision data constrains mixings between ordinary and exotic fermions, large extra dimensions, new four-fermion operators, and leptoquark bosons [2].

Gauge unification is predicted in GUTs and some string theories. The simplest non-supersymmetric unification is excluded by the precision data. For the MSSM, and assuming no new thresholds between \( 1 \text{ TeV} \) and the unification scale, one can use the precisely known \( \alpha \) and \( \hat{s}_Z^2 \) to predict \( \alpha_s = 0.130 \pm 0.010 \) and a unification scale \( M_G \sim 3 \times 10^{16} \text{ GeV} \) [39]. The \( \alpha_s \) uncertainties are mainly theoretical, from the TeV and GUT thresholds, etc. \( \alpha_s \) is high compared to the experimental value, but barely consistent given the uncertainties. \( M_G \) is reasonable for a GUT (and is consistent with simple seesaw models of neutrino mass), but is somewhat below the expectations \( \sim 5 \times 10^{17} \text{ GeV} \) of the simplest perturbative heterotic string models. However, this is only a 10% effect in the appropriate variable \( \ln M_G. \) The new exotic particles often present in such models (or higher Kač-Moody levels) can easily shift the \( \ln M_G \) and \( \alpha_s \) predictions significantly, so the problem is really why the gauge unification works so well. It is always possible that the apparent success is accidental (cf., the discovery of Pluto).

**CONCLUSIONS**

The precision \( Z \)-pole, LEP 2, WNC, and Tevatron experiments have successfully tested the SM at the 0.1% level, including electroweak loops, thus confirming the gauge principle, SM group, representations, and the basic structure of renormalizable field theory. The standard model parameters \( \sin^2 \theta_W, m_t, \) and \( \alpha_s \) were precisely determined. In fact, \( m_t \) was successfully predicted from its indirect loop effects prior to the direct discovery at the Tevatron, while the indirect value of \( \alpha_s, \) mainly from the \( Z \)-lineshape, agreed with more direct QCD determinations. Similarly, \( \Delta \alpha_{\text{had}}^{(5)}(M_Z) \) and \( M_H \) were constrained. The
indirect (loop) effects implied $M_H \lesssim 215$ GeV, while direct searches at LEP 2 yielded $M_H > 114.5$ GeV, with a hint of a signal at 116 GeV. This range is consistent with, but does not prove, the expectations of the supersymmetric extension of the SM (MSSM), which predicts a light SM-like Higgs for much of its parameter space. The agreement of the data with the SM imposes a severe constraint on possible new physics at the TeV scale, and points towards decoupling theories (such as most versions of supersymmetry and unification), which typically lead to 0.1% effects, rather than TeV-scale compositeness (e.g., dynamical symmetry breaking or composite fermions), which usually imply deviations of several % (and often large flavor changing neutral currents). Finally, the precisely measured gauge couplings were consistent with the simplest form of grand unification if the SM is extended to the MSSM.

ACKNOWLEDGMENTS

It is a pleasure to thank my collaborators, especially Jens Erler, for fruitful interactions. This work was supported in part by a Department of Energy grant DOE-EY-76-02-3071.

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