Recent Developments in Precision Electroweak Physics*

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Abstract

Developments in precision electroweak physics in the two years since the symposium are briefly summarized.

1 Introduction

The precision electroweak program has been remarkably successful in demonstrating: (a) that the standard electroweak model is correct to first approximation, verifying the gauge principle, the $SU(2) \times U(1)$ group, and the representations; (b) that the QED, electroweak, QCD, and mixed radiative corrections are correct, verifying the validity of renormalizable gauge theories; (c) determining such standard model parameters as the weak angle and predicting $m_t$, $\alpha_s$, and $M_H$; and (d) severely constraining possible new physics at the TeV scale to be of the decoupling type, such as supersymmetry. All of these issues were thoroughly explored in the talks and written versions of the Alberto-Fest, held at NYU in October 2000. It is the purpose of this note to mention a few of the major developments in the subsequent two years. More details may be found in [1, 2, 3].

*This is an update on recent developments, prepared for the publication of the Proceedings of Alberto Sirlin Symposium, New York University, October 2000.
2 New inputs and anomalies

There have been a number of recent important results, some hinting at the possibility of new physics.

- The direct determination of the W mass from CDF, DØ, and UA2, currently 80.454(59) GeV [2, 4] has for some time been on the high side of the standard model fit prediction of 80.391(18) GeV [4]. However, the recent LEP2 determination of 80.450(39) [2] is also slightly high, leading to a combined value of 80.451(33) GeV. This is only 1.8σ above the best fit prediction, but contributes to the small predicted value for the Higgs mass.

- Preliminary analysis of the LEP2 data at energies in excess of 206 GeV indicated evidence for the Higgs boson at around 115 GeV. The significance of the signal has been considerably reduced in the final analyses [5], although there is still a hint, especially in the ALEPH four-jet data [6]. The LEP Higgs working group now quotes a preliminary combined lower limit \( M_H > 114.4 \) GeV at 95% cl on the standard model Higgs.

- There is a new estimate of \( \alpha_s \) from the \( \tau \) lifetime [4, 7], 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 0.0994(17), which is 2.6σ below the standard model global fit value of 0.1038(8). On the other hand, the SLD value for the related quantity \( A_b = 0.922(20) \) (see the appendices in [8] for the definitions) is only 0.6σ below the expected 0.9347(1), and the hadronic branching fraction \( R_b = 0.2165(7) \), which at one time appeared anomalous, is now only 1.1σ 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 [4, 10]; or to the mixing of the \( b_R \) with exotic quarks [4, 11], such as with an \( SU(2) \) doublet involving a heavy \( B_R \) quark and a charge \(-4/3\) partner [11]. There is a strong correlation between \( A_{FB}(b) \) and the predicted Higgs mass \( M_H \) in the global fits. It has been emphasized [12] 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 LEP2. 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 [13], which modify the radiative corrections and allow an acceptable $M_H$.

- The NuTeV collaboration at Fermilab [14] have reported the results of their deep inelastic measurements of $\nu_{\mu} N \rightarrow \nu_{\mu} X$ using their sign-selected beam. They are able to 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 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 [14]; an asymmetric strange sea [15], though NuTeV’s data seems to favor the wrong sign for this effect; nuclear shadowing effects [16]; or next to leading order QCD effects [15].

More exotic interpretations could include a heavy $Z'$ boson [4, 15], 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 [17, 18], 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 $N_{\nu} = 3$) [1, 4]. 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 [18]. However, such mixings would also lead to a lower value for $|V_{ud}|$, significantly aggravating the universality problem discussed below.

- The Brookhaven $g-2$ experiment has reported a precise new value [19] 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, there is now a small discrepancy, with the experimental $a_{\mu}$ larger than the standard model expectation by $(26 \pm 11) \times 10^{-10}$, a $2.6\sigma$ effect. The value and uncertainty in this vacuum
polarization are still controversial\(^1\), so it is hard to know how seriously to take the discrepancy. One obvious candidate for a new physics explanation would be supersymmetry \(^{20}\) with relatively low masses for the relevant sparticles and high \(\tan \beta\) (roughly, one requires an effective mass scale of \(\tilde{m} \sim 55\) 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 \(\alpha\) to the \(Z\) pole \(^{21}\), leading to a slight reduction in the predicted Higgs mass when \(a_\mu\) is included in the global fit assuming the standard model.

- A few years ago there was an apparent 2.3\(\sigma\) discrepancy between the measured value of the effective (parity-violating) weak charge \(Q_W(Cs)\) measured in cesium \(^{22}\), and the expected value. In particular, 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\%. It was subsequently pointed out, however, that there was a significant contribution from the Breit (magnetic) interaction between two electrons \(^{23}\), reducing the discrepancy. Further calculations of the \(O(Z\alpha^2)\) radiative corrections associated with the vacuum polarization in the nuclear Coulomb field reinstated the discrepancy, yielding \(Q_W = -72.12(28)(34)\) \(^{24}\) and \(-72.18(29)(36)\) \(^{25}\), which are respectively 2.2 and 2.0\(\sigma\) above the expected \(-73.09(3)\). An even more recent calculation of the electron line corrections \(^{26}\) (including some estimated higher order effects) was surprising large, yielding \(-72.83(29)(39)\), in agreement with the standard model. The situation is confusing, and it is not certain whether the last word has been written, but clearly at this point there is no evidence for new physics.

- 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 \(0^+\rightarrow0^+\) transitions, currently yielding \(|V_{ud}| = 0.9740(5)\) \(^{27}\). Combining with \(|V_{us}|\) from kaon and hyperon decays and \(|V_{ub}|\) from \(b\) decays, this yields a 2.3\(\sigma\) discrepancy \(\Delta = 0.0032(14)\). It is unlikely that the uncertainties in \(|V_{us}|\) or \(|V_{ub}|\) could be responsible, suggesting either the presence of unaccounted-for new physics, or, possibly, effects from higher order isospin violation such as nu-

\(^1\)There are also uncertainties in the smaller hadronic light by light diagram. An unfortunate sign error increased the apparent discrepancy with the experimental value at an earlier stage, but this has now been corrected.
clear 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 [28]. 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 3σ 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.) On the other hand, 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 [29], especially if the right-handed neutrinos are Majorana and too heavy to be produced in the decays.

- The LEP and SLC Z-pole experiments are the most precise tests of the standard electroweak theory, but they are blind 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 [30], and in the QWEAK polarized electron experiment at Jefferson Lab [31].

3 Fit Results

As of June, 2002, the result of the global fit is [4]

$$ M_H = 86^{+49}_{-32} \text{ GeV}, $$

$$ m_t = 174.2 \pm 4.4 \text{ GeV}, $$

$$ \alpha_s = 0.1210 \pm 0.0018, $$

$$ \hat{\alpha}(M_Z)^{-1} = 127.922 \pm 0.020 $$

$$ \hat{s}_Z^2 = 0.23110 \pm 0.00015, $$

$$ \hat{s}_t^2 = 0.23139 \pm 0.00015, $$

$$ \hat{s}_W^2 = 0.22277 \pm 0.00035 $$

$$ s_{MZ}^2 = 0.23105 \pm 0.00008 $$
\( \chi^2 / \text{d.o.f.} = 49.0/40(15\%) \) \( (1) \)

This is in generally good agreement with the fit of the LEP Electroweak Working Group of May, 2002 \[2\],

\[
\begin{align*}
M_H &= 85^{+54}_{-34} \text{ GeV}, \\
\alpha_s &= 0.1183 \pm 0.0027, \\
m_t &= 174.7^{+4.5}_{-4.3} \text{ GeV} \\
\tilde{s}_t^2 &= 0.23137 \pm 0.00015, \\
\tilde{s}_W^2 &= 0.22272 \pm 0.00036,
\end{align*}
\]

\( (2) \)

up to understood effects associated with the input data set, higher order terms, and the value of \( \Delta \alpha_{\text{had}}^{(5)}(M_Z) \). The agreement is especially impressive since the LEPEWWG analysis utilized expressions computed in the on-shell scheme, while the analysis in \( \[1\] \) used \( \overline{\text{MS}} \). The slightly higher value \( \alpha_s = 0.1210 \pm 0.0018 \) in \( \[1\] \) is due in part to the inclusion of the new \( \tau \) lifetime result \( \[7, 4\] \).

(Without it, one would obtain \( \alpha_s = 0.1200 \pm 0.0028 \).) These values for \( \alpha_s \) are in reasonable agreement with the previous world average \( \alpha_s = 0.1172(20) \), which includes other determinations, most of which are dominated by theoretical uncertainties \( \[32\] \). The \( Z \)-pole value is insensitive to oblique new physics, but is very sensitive to non-universal new physics, such as those which affect the \( Z \bar{b} \bar{b} \) vertex.

The prediction for the Higgs mass from indirect data, \( M_H = 86^{+48}_{-32} \text{ GeV} \), should be compared with the direct LEP2 limit \( \[3\] \) \( M_H \gtrsim 114.4(95\%) \text{ GeV} \). 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 \( 150 \text{ GeV} \) in generalizations. Including the direct LEP2 exclusion results, one finds \( M_H < 215 \text{ GeV} \) at 95\%. The probability distribution for \( M_H \), including both direct and indirect constraints and updated from the analysis in \( \[33\] \), is shown in Figure \( \[1\] \).

\( M_H \) 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 \( A_{FB}(b) \) \( \[12\] \).

\[\text{\footnotesize See also the study in \[34\]}\]
4 Beyond the Standard Model

The \( \rho_0 \) or \( S, T, U \) 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:

\[
\begin{align*}
S &= -0.14 \pm 0.10(-0.08) \\
T &= -0.15 \pm 0.12(+0.09) \\
U &= 0.32 \pm 0.12(+0.01) \quad (2.6\sigma)
\end{align*}
\]
for $M_H = 115.6$ (300) 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 $M_H = 73^{+106}_{-34}$ 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 $M_H < 570$ 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 $T = -0.01 \pm 0.11$.

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