Fermilab Library
0 1160 0025551 7
NYU-TH-93-06-04

NYU-Th-93/06/04

STATUS OF THE STANDARD ELECTROWEAK MODEL[1]

A. SIRLIN
Department of Physics, New York University
New York, NY 10012, USA

1. Introduction

The focus of this contribution is in the area of precision electroweak physics. During recent years there has been considerable improvement in the experimental accuracy. At LEP it is often $\sim$ few tenths of a percent while at low energies it frequently reaches $\sim$0.1% (as in nuclear β decay). There has also been considerable progress on the theoretical side. Since 1980, simple strategies to renormalize the theory have been developed. These formulations keep a close contact with experimental observables and have permitted the systematic investigation of higher order corrections to allowed processes. The objectives are: (i) to verify the Standard Model (SM) at the level of its quantum corrections, (ii) to constrain m_t, m_H, (iii) to search for deviations that may signal the existence of new physics.

2. Basic Parameters

There are at present three very accurate parameters that play a basic role in electroweak physics: the fine structure constant, α, known within an uncertainty $\Delta\alpha = 0.045\,ppm$; $G_\mu = 1.16639(2) \times 10^{-5}\,GeV^{-2}$, derived from the muon lifetime ($\Delta G_\mu = 17ppm$); $m_Z = 91.187 \pm 0.007\,GeV$, accurately measured at LEP ($\Delta m_Z = 77ppm$). This m_Z determination became possible after the energy of the LEP beams was calibrated by the method of resonant depolarization.

The instability of Z^o leads to an interesting conceptual and practical problem regarding the theoretical definition of its mass. One considers the Z^o propagator:

$$D^{Z^o}_{\mu\nu}(q) = -\frac{ig_{\mu\nu}}{q^2 - m_o^2 - A(s)} + \dots , \tag{1}$$

where m_o is the bare mass, $A(s)$ the conventional self-energy, (which includes γZ mixing effects starting in $O(\alpha^2)$) and the ellipses represent terms proportional to

[1]Invited talk presented at SUSY-93, "International Workshop on Supersymmetry and Unification of Fundamental Interactions," Northeastern University, Boston, MA, March 29-April 1, 1993

$q_\mu q_\nu$. The traditional, on-shell definition of mass is

$$m^2 = m_o^2 + R_e A\left(m^2\right) \ . \tag{2}$$

The rationale behind Eq. (2) is easy to see: counterterms in field theory are real and the on-shell subtraction leads to a gauge invariant definition in $O(\alpha)$. But what about higher orders? There is an alternative definition that goes back to the old S-Matrix Theory. One considers the complex-valued position of the pole

$$\bar{s} = m_o^2 + A\left(\bar{s}\right) \ , \tag{3}$$

which is expected to be gauge invariant because it represents the position of a singularity of the analytically continued S-matrix. The idea of defining m_{Z^o} and Γ_Z in terms of the real and imaginary parts of $\bar{s}$ has been recently proposed by a number of people.[1,2] Parametrizing $\bar{s} = m_2^2 - i m_2 \Gamma_2$, one identifies m_2 and Γ_2 with the mass and the width, respectively, although other definitions of mass involve combinations of m_2^2 and Γ_2^2. It has been recently shown that the on-shell definition m is gauge-dependent starting in $O(\alpha^3)$ for a wide class of gauges and in $O(\alpha^2)$ in the complementary set.[2] A relevant question is what is the mass measured at LEP. In Ref. [2] the idea was proposed of replacing $m^2 \to m_1^2 \equiv m_2^2 + \Gamma_2^2$ (m and m_1 are very close numerically through $O(\alpha^2)$). In terms of m_1 the propagator exhibits the q^2-dependent Breit-Wigner resonance employed in LEP analyses. Thus, m_1, a theoretically satisfactory concept, can be identified with the mass measured at LEP. The choice between m_1 and $m_2 = m_1 - 34\,MeV$ is a matter of convention, but m_1 is more appropriate to describe low energy physics.

3. m_W and $\sin^2\hat{\theta}_W(m_Z)$

Knowing α, G_μ, and m_Z one can evaluate m_W and the $\overline{MS}$ parameter $\hat{s}^2 \equiv \sin^2\hat{\theta}_W(m_Z)$ as functions of m_t and m_H. Defining $\sin^2\theta_W = 1 - m_W^2/m_Z^2 = s^2$, one has in the on-shell scheme,[3]

$$s^2 c^2 = (A^2/m_Z^2)(1 - \Delta r)^{-1} \ , \tag{4}$$

where $A^2 = \pi\alpha/(\sqrt{2}G_\mu) = (37.2802\,GeV)^2$, while in the $\overline{MS}$ framework[4] the corresponding relation is

$$\hat{s}^2\hat{c}^2 = (A^2/m_Z^2)(1 - \Delta\hat{r})^{-1} \ . \tag{5}$$

The quantity Δr, a basic correction that leads to the evaluation of m_W, is a physical observable and can be directly measured. The parameter $\hat{s}^2$ is very convenient to discuss LEP physics[4] and can be obtained almost directly from the on-resonance asymmetries with the application of very small radiative corrections. It is crucial for

GUTs studies. The leading asymptotic behaviors of Δr and $\Delta\hat{r}$ are $\sim m_t^2$ but the corresponding coefficient for Δr is enhanced by a factor $c^2/s^2 \approx 3.4$. In the $\overline{MS}$ scheme there is another basic correction, $\Delta\hat{r}_W$, which occurs in the relation

$$\hat{s}^2 = (A^2/m_W^2)(1 - \Delta\hat{r}_W)^{-1} . \tag{6}$$

Unlike Δr and $\Delta\hat{r}$, the leading m_t behavior of $\Delta\hat{r}_W$ is logarithmic. On the other hand, the large m_H dependence of the three corrections is logarithmic. They are not independent: $\Delta\hat{r}$ and $\Delta\hat{r}_W$ can be used to calculate Δr.[4]

4. Supersymmetric Unification

An early application of $\Delta\hat{r}$ and $\Delta\hat{r}_W$ was the fairly accurate estimate of $\hat{s}^2$ almost as soon as LEP started operations. In fact, the first two papers of Ref. (4) led, by October of 1989, to a value $\hat{s}^2 = 0.2327 \pm 0.0015$, while a very recent global analysis by Langacker[5] gives $\hat{s}^2 = 0.2328 \pm 0.0007$. It was pointed out in the early papers[4] that these values are nicely consistent with the simplest (*i.e.* $SU(5)$ or one-step) SUSY GUT prediction. Since that time, the GUT predictions have been reexamined by several groups[6] taking into account reasonable ranges and splittings in the supersymmetric spectrum[7] and uncertainties associated with m_t and threshold corrections. Using $\hat{\alpha}^{-1}(m_Z) = 127.9 \pm 0.2$ and $\hat{\alpha}_s(m_Z) = 0.12 \pm 0.01$, Langacker[5] cites the minimal SUSY GUT prediction

$$\hat{s}^2 = 0.2334 \pm 0.0025 \pm 0.0025 \quad \textit{(SUSY GUT)} , \tag{7}$$

where the first error is associated with $\Delta\hat{\alpha}$ and $\Delta\hat{\alpha}_s$, and the second with uncertainties from the superspectrum, high-scale thresholds, and possible non-renormalizable operators. Instead, for the non supersymmetric $SU(5)$-like GUT one has

$$\hat{s}^2 = 0.2100 \pm 0.0025 \pm 0.0007 \quad \textit{(GUT)} . \tag{8}$$

It is actually better to use $\hat{\alpha}(m_Z)$ and $\hat{s}^2$ as inputs and predict $\hat{\alpha}_s(m_Z)$. One obtains[5] $\hat{\alpha}_s(m_Z) = 0.125 \pm 0.002 \pm 0.009$ (SUSY GUT) and $\hat{\alpha}_s(m_Z) = 0.072 \pm 0.001 \pm 0.001$ (GUT). The very nice agreement between the experimental values of $\hat{s}^2$ (or $\hat{\alpha}_s$) and the predictions have been taken by many as a harbinger of supersymmetric unification.

5. Leading Higher Order Corrections

Recent evaluations of Δr, $\Delta\hat{r}$, $\Delta\hat{r}_W$ include terms of $O(\alpha)$, $O(\alpha^n \ell n^n(m_Z/m_f))$, $O(\alpha^2 \ell n(m_Z/m_f))$,[3,4] where m_f is a generic fermion mass, $O[\alpha^2(m_t^2/m_W^2)^2]$,[8] and QCD effects.[9] The latter involve perturbative $O(\hat{\alpha}\hat{\alpha}_s)$ contributions due to gluon exchange in the vacuum polarization functions,[10] and $t - \bar{t}$ threshold effects. The threshold contributions to the imaginary parts of the self-energies have been studied with two methods: the resonance approach[11] and the Green function formulation.[12] In order to study the real parts, dispersion relations that explicitly satisfy relevant

Ward identities have been applied.[13] The QCD corrections depend on the precise definition of m_t. Current studies employ the pole or on-shell definition, in which case the large m_t behavior of $\Delta\hat{r}$ is

$$\Delta\hat{r} \sim -\frac{3\alpha}{16\pi\hat{s}^2\hat{c}^2}\frac{m_t^2}{m_Z^2}\left[1-\frac{2\hat{\alpha}_s(m_t)}{3\pi}\left(\frac{\pi^2}{3}+1\right)\right] , \tag{9}$$

with analogous results for Δr. The QCD correction in Eq. (9) is $\approx -10\%$ and this roughly increases the predicted m_t by $\approx 5\%$. It is a curious fact that all the recent refinements involving two-loop effects, namely $O(\hat{\alpha}\hat{\alpha}_s)$, $t-\bar{t}$ threshold and $O(\alpha^2(m_t^2/m_W^2)^2)$ increase m_t, leading to $\Delta m_t \approx 16.8\ GeV$ for $m_t = 200\ GeV$ and $m_H = 250\ GeV$. The $O(\hat{\alpha}\hat{\alpha}_s m_t^2/m_W^2)$ corrections to $Z^o \to b+\bar{b}$ have also been computed recently[14] and turn out to be $\approx -9\%$. The contribution of Degrassi is particularly novel as it involves the application of current algebra methods to two-loop graphs, a technique that greatly simplifies some calculations.

The corrections Δr and $\Delta\hat{r}$ lead, via Eqs. (4,5) to predictions of m_W and $\hat{s}^2$, as functions of m_t and m_H. Comparing these values with the experimental determinations of m_W and $\hat{s}^2$ imply significant constraints on m_t.

6. Global Analyses

Langacker's very recent analysis[5] incorporates nearly final results for the 1991 LEP run and leads to

$$m_t = 150^{+19+15}_{-24-20}\ GeV , \tag{10}$$

where the central value corresponds to $m_H = 300\ GeV$, the first error is experimental and the second arises from the assumption $60\ GeV < m_H < 1\ TeV$. He also reports

$$\hat{s}^2 = 0.2328 \pm 0.0007 , \tag{11}$$

$$s^2 = 0.2267 \pm 0.0024 . \tag{12}$$

Another very important result is $N_\nu = 3.004 \pm 0.035$, where N_ν is the number of non-sterile neutrinos. The comparison of the data with the SM model predictions corresponding to Eq. (10) and the above range for m_H is rather impressive (see Table 1.) One has 11 independent on resonance observables (m_Z, Γ_Z, $R = \Gamma_{had}/\Gamma_{\ell\bar{\ell}}$, $\sigma_p^h(nb)$, $\Gamma_{b\bar{b}}$, $A_{FB}(\mu)$, $A_{pol}(\tau)$, $A_e(P_\tau)$, $A_{FB}(b)$, $A_{FB}(c)$, measured at LEP, and A_{LR}, measured at SLC). Aside from the above, the data includes m_W/m_Z from UA2, m_W from CDF, s^2 determined from deep inelastic neutrino scattering (νN), $Q_W(Cs)$ (the weak charge in Cs) and the couplings g_V^e and g_A^e derived from $\overset{(-)}{\nu}_\mu + e \to \overset{(-)}{\nu}_\mu + e$ by CHARM II. The m_Z value and $\hat{\alpha}_s(m_Z) = 0.12 \pm 0.01$, determined from event topologies, τ decay, deep inelastic scattering, Υ and J/ψ, are used as inputs. All the

observables lie within 1σ of the theoretical predications with the exception of R (1.3σ) and $Q_W(Cs)$ (1.4σ). Furthermore, one should remember that these two quantities are affected by additional QCD and atomic theory uncertainties, respectively.

In the case of the minimal supersymmetric model (MSSM), it is expected that the additional radiative corrections associated with the supersymmetric partners are small provided that the five mass parameters that characterize the model are much larger than m_Z.[15] In that case, the supersymmetric partners become very massive and effectively decouple. The radiative corrections become those of the SM with a light Higgs, $m_H < 150\,GeV$. In this limit, taking $60\ GeV < m_H < 150\ GeV$, the fit to the electroweak data gives[5]

$$m_t = 134^{+23}_{-28} \pm 5\,GeV \quad (MSSM)\,, \tag{13}$$

where the central value is for $m_H = m_Z$ and the second error again reflects the allowed m_H range. Even if the supersymmetric partners are not regarded as infinitely heavy, the decoupling limit provides a lower bound for the MSSM prediction of the relevant observables.[15] A significant contribution to $\Delta\rho$ may arise if the stop and sbottom scalars have a mass difference comparable to their mean mass, a scenario that requires a non too heavy stop.[15]

An even more recent global analysis of the SM by Schaile,[16] based on LEP, m_W, m_W/m_Z and νN data, gives

$$m_t = 155^{+17+17}_{-17-20}\ GeV\ , \tag{14}$$

$$\sin^2\theta^{lept}_{W_{eff}} = 0.2328 \pm 0.0005 \pm 0.0002\ . \tag{15}$$

This fit incorporates preliminary 1992 LEP results. The effective angle $\sin^2\theta^{lept}_{W_{eff}}$ and $\hat{s}^2$ are conceptually different but, by a fortuitous cancellation of radiative corrections, they are very close numerically. A very interesting result of the LEP analysis is that, assuming the SM, it leads to an accurate indirect determination $m_W = 80.22 \pm 0.12 \pm 0.02\ GeV$,[16] which is in very good agreement with the direct measurement $m_W = 80.22 \pm 0.26\ GeV$ from CDF and UA2 (combined with the LEP value for m_Z). We note that the indirect determination is considerably more precise.

From the present data it is not possible to constrain m_H. An interesting question is to what extent a future determination of m_t with a $\pm 10\,GeV$ error might help. One finds[5] that such a scenario will reduce the m_H upper bound if the central value m_t is found in the range $100\ GeV < m_t < 150\ GeV$. For example, for $m_t = 130\ GeV$ the 68 and 90% CL ranges would be $60\ GeV \lesssim m_H \lesssim 340\ GeV$ and $60\ GeV \lesssim m_H \lesssim 700\ GeV$, respectively. For $m_t \gtrsim 150\ GeV$, one only has the theoretical upper bound. For $m_t \gtrsim 160\ GeV$, lower bounds emerge. For example, for $m_t = 180\,GeV$, the 68

and 90% CL ranges are 340 $GeV \lesssim m_H \lesssim 1\ TeV$ and 140 $GeV \lesssim m_H \lesssim 1\ TeV$, respectively. Qualitatively, lower (higher) m_t values favor lower (higher) m_H, which can be partially understood from the fact that the leading m_t and m_H dependent behaviors in both Δr and $\Delta\hat{r}$ are of opposite sign. However, it should be stressed that these m_H bounds are very sensitive to small changes in the electroweak data. Thus, they may be modified significantly as the information becomes more precise.

7. S, T, and U Parameters

Assume that there is new physics associated with a high mass scale. It may affect the quantum corrections, especially through self-energy contributions. The idea has been proposed to parameterize the new physics in terms of three amplitudes, S, T, and U.[17,18] In the $\overline{MS}$ scheme we have[18]

$$\Delta\hat{r} = (\Delta\hat{r})_{SM} + \frac{\alpha}{4\hat{s}^2\hat{c}^2} S_Z - \alpha T \ , \tag{16}$$

$$\Delta\hat{r}_W = (\Delta\hat{r}_W)_{SM} + \frac{\alpha}{4\hat{s}^2} S_W \ , \tag{17}$$

$$\frac{\alpha}{4\hat{s}^2\hat{c}^2} S_Z = Re\left[\frac{A_{ZZ}(m_Z^2) - A_{ZZ}(0)}{m_Z^2} - A'_{\gamma\gamma}(0) - \frac{(\hat{c}^2 - \hat{s}^2)}{\hat{c}\hat{s}} A'_{\gamma Z}(0)\right]^{new}_{\overline{MS}} \ , \tag{18}$$

$$\frac{\alpha}{4\hat{s}^2} S_W = Re\left[\frac{A_{WW}(m_W^2) - A_{WW}(0)}{m_W^2} - A'_{\gamma\gamma}(0) - \frac{\hat{c}}{\hat{s}} A'_{\gamma Z}(0)\right]^{new}_{\overline{MS}} \ , \tag{19}$$

$$\alpha T = Re\left[\frac{A_{WW}(0)}{m_W^2} - \frac{A_{ZZ}(0)}{m_Z^2}\right]^{new}_{\overline{MS}} \ , \tag{20}$$

where the A's are unrenormalized self-energies defined according to Ref. [3], the primes indicate derivatives with respect to q^2 (q_μ is the external four momentum), new refers to new physics contributions and $\overline{MS}$ means that the pole terms have been subtracted and the 't Hooft mass scale μ has been set equal to m_Z. This is equivalent to the formulation of Marciano and Rosner.[18] However, our notation is slightly different, as the subtraction terms are given explicitly in Eqs. (18,19). Alternatively, one defines $S \equiv S_Z$, $U \equiv S_W - S_Z$. T and U are primarily sensitive to isodoublet mass splittings. Generally, $U << T$. S is sensitive to contributions from degenerate fermions. The amplitudes $(\Delta\hat{r}_W)_{SM}$ and $(\Delta\hat{r})_{SM}$ are calculated at standard values of m_t and m_H. Then S, T, and U parametrize hypothetical effects of heavy unknown particles, as well as departures of m_t and m_H from the standard values. The modification of $\Delta\hat{r}$ and $\Delta\hat{r}_W$ induces the shifts

$$\hat{s}^2 = (\hat{s}^2)_{SM} + \frac{\hat{\alpha}}{4(\hat{c}^2 - \hat{s}^2)}[S - 4\hat{s}^2\hat{c}^2 T] \ , \tag{21}$$

$$m_W = (m_W)_{SM}\left[1 + \frac{\hat{\alpha}\hat{c}^2}{2(\hat{c}^2-\hat{s}^2)}T + \frac{\hat{\alpha}}{8\hat{s}^2}U - \frac{\hat{\alpha}S}{4(\hat{c}^2-\hat{s}^2)}\right] . \tag{22}$$

To obtain the dependence of the observables on S and T one inserts Eq. (21) in neutral current amplitudes and multiply them by $\rho(0)|_{new} = 1 + \hat{\alpha}T$. In particular, the weak charge $Q_W(Cs) \propto S + 0.006T$ and is therefore especially sensitive to S.[18]

A very recent determination by Langacker[19] gives $S = -0.29 \pm 0.46$, $T = 0.05 \pm 0.43$, $U = 0.37 \pm 0.93$ for standard values $m_t = m_H = m_Z$. By comparison, a fourth generation of degenerate fermions gives $S \approx 4/(6\pi) = 0.21$, while technicolor models roughly contribute $S \approx (0.05 \pm 0.10)N_T N_D + 0.12$ where N_T and N_D are the number of technicolors and isodoublets, respectively. Thus, for one generation with $N_T = N_D = 4$ one expects $S \approx 0.9$ to 1.7. If S turns out to be negative as errors decrease, it may signal an additional Z^o. $S < 0$ may be due to a value of m_W larger than $(m_W)_{SM}$, and this occurs in a class of theories with additional Z^o's.

An interesting question is whether the m_t upper bound can be evaded by invoking new physics. Over most of parameter space, additional fermion generations of the usual kind give contributions to Δr or $\Delta\rho$ of the same sign as m_t; thus, the m_t bound becomes sharper. However, in models in which, aside from m_{Dirac}, a fourth generation ν_R is endowed with m_{Maj} of $O(G_\mu^{-1/2})$,[20] the contributions to $\Delta r(\Delta\rho)$ are not bounded above (below) and there can be large effects of opposite sign to the m_t contributions.[21] It was estimated that the bound could be increased in such models by as much as $\approx 31\ GeV$. The same scenario was tried to obtain $S < 0$.[22] This indeed is possible, but only mildly negative values were obtained. Another scenario where the m_t bound can be evaded is a model with two Higgs doublets endowed with arbitrary masses.[23]

8. Universality of the Weak Interactions

8.1 Lepton Couplings

To $O(\alpha^o)$ the ratio $Re/\mu = \Gamma(\pi \to e\bar{\nu}_e + e\bar{\nu}_e\gamma)/\Gamma(\pi \to \mu\bar{\nu}_\mu + \mu\bar{\nu}_\mu\gamma)$ is not affected by strong interactions.[24] The $O(\alpha)$ corrections were evaluated long ago[25] and turned out to be $\approx 3.7\%$. However, because of strong interaction effects, it was not clear whether these calculations are realistic. General and complementary arguments advanced in Refs. [26,27] indicate that the $O(\alpha)$ calculation is very precise. Recent experiments give $R_{exp} = (1.2265 \pm 0.0034 \pm 0.0044) \times 10^{-4}$ (TRIUMF)[28] and $R_{exp} = (1.235 \pm 0.003 \pm 0.004) \times 10^{-4}$ (SIN),[29] while an update by Marciano leads to $R_{TH} = (1.2345 \pm 0.0010) \times 10^{-4}$. From here one deduces[30]

$$\frac{g_e}{g_\mu} = 0.9985 \pm 0.0015 , \tag{23}$$

an impressive verification of electron-muon universality. Using

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = Br(\tau \to e + \nu + \bar{\nu})\frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 , \tag{24}$$

and assuming $e - \mu$ universality, the LEP data leads to $(g_\tau/g_\mu) = 0.996 \pm 0.008$.[16] If this is combined with non LEP data, there is a difference with unity of $\approx 1.5\sigma$. There are also impressive tests of universality in the neutral currents. On the basis of earlier LEP data, one has $g_a^e/g_a^\mu = 1.003 \pm 0.003$, $g_a^\tau/g_a^\mu = 1.001 \pm 0.004$,[31] where the g_a's are the axial vector neutral current leptonic couplings.

8.2 Unitarity of the CKM Matrix

The present statement of universality is the unitarity of the CKM matrix. The most precise test is the prediction

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 . \tag{25}$$

V_{ud} is extracted from the ratio of decay rates of the superallowed Fermi transitions, such as ^{14}O, and the muon (G_V/G_μ). If only the classical Fermi Coulomb correction to β decay were relevant, the r.h.s. would be ≈ 1.039 and the SM would not be tenable. However, there are large radiative corrections to β-decay not present in μ decay. The leading corrections are[32]

$$P = P^o\left\{1 + \frac{3\alpha}{2\pi}\left[\ell n\left(\frac{m_Z}{2E_m}\right) + 2\overline{Q}\ell n\left(\frac{m_Z}{M}\right) + \cdots\right]\right\} , \tag{26}$$

where E_m is the end point energy of the positron, $\overline{Q} = 1/6$ the average charge of the underlying quarks in the charged current (u and d) and M a hadronic mass $\sim$ 1 GeV. The large logarithm leads to a correction $\approx 3.45\%$, decreases the values of V_{ud} extracted from experiment and literally rescues the SM! A current algebra formulation of the radiative corrections is necessary to control the effect of the strong interactions.[32] Other corrections are $\sim$ few tenths of a percent. At that level, there are some nuclear theory uncertainties and the current value is in the range $0.9734 \lesssim V_{ud} \lesssim 0.9750$.[33] The higher values lead to very good agreement with Eq. (25) but the lower bound falls short by 2.4 times the estimated error, which is mainly theoretical. If $\Sigma_i|V_{ui}|^2 < 1$ $(1 = d, s, b)$ were established, it may be a signal of $L - R$ symmetry. In "manifest" $L - R$ symmetry models $G_V/G_\mu = (1 - \zeta)V_{ud}$,[34] where ζ is the mixing angle between W_L and W_R, and ζ can restore agreement with unitarity. Precision measurements of ^{10}C and $\pi^\pm\beta$ decays may help clarify the situation.

8.3 Neutron Decay

Using τ_n one can determine $G_V^2 + 3G_A^2$. A recent measurement of A,[35] the coefficient that describes the angular distribution of the electron relative to the neutron spin, has lowered the world average to $G_A/G_V = 1.257 \pm 0.003$. Combining the two pieces of information one obtains $V_{ud} = 0.9813 \pm 0.0021$ and $\Sigma_i |V_{ui}|^2 = 1.0116 \pm 0.0041$, 2.8σ above unity. This V_{ud} differs from the value extracted from the Fermi transitions by more than 3σ. Experimental clarification is needed. Neutron β decay is a fundamental process of the weak interactions and should be studied with as much precision as possible!

9. Conclusions

(i) At the present level of accuracy, the SM describes very well the results of a large number of laboratory experiments, over a wide range of energy scales, $0 \lesssim |q^2| \lesssim m_Z^2$. The agreement is rather impressive, but there may be surprises in the future, as the accuracy improves.

(ii) In the universality question, there are problems that require further scrutiny: neutron β decay, ^{10}C and $\pi^{\pm}\beta$ decays.

(iii) Simple renormalization strategies have been developed since $\approx$ 1980 which have been applied systematically to study the radiative corrections to a large variety of phenomena. They play an important rôle in current analyses.

(iv) A very recent global fit[5] leads to the results of Eqs. (10-12) and to the 95% CL constraint $m_t < 197\ GeV$ (for $m_H = 1\ TeV$). The even more recent fit of Ref. (16) leads to Eq. (14).

(v) The $\hat{s}^2$ value (Eq. (11)) is consistent with the simplest scenario of supersymmetric unification.

(vi) Notwithstanding the current successes of the SM as an effective, renormalizable theory, there remains a plethora of unsolved, fundamental problems: the mechanism of symmetry breaking, the origin of the mass spectrum and the number of generations, the possibility of GUTs and the incorporation of gravity, the solar neutrino deficit, the detailed understanding of CP violation and probably others that will unfold as we continue our quest.

10. Acknowledgements

The author is indebted to P. Langacker for private communications and making available to him the results of his global analysis. This work was supported in part by the National Science Foundation under Grant No. PHY-9017585.

11. References

1. M. Consoli and A. Sirlin, in *Physics at LEP*, edited by J. Ellis and R. Peccei (CERN Report No. 86-02, 1986), Vol. 1, p. 63 ff; S. Willenbrock and G. Valencia, *Phys. Lett.* **B259**, 373, (1991); R.G. Stuart, *Phys. Lett.* **B262**, 113 (1991);

ibid. **B272**, 353 (1991); T. Bhattacharya and S. Willenbrock, Brookhaven National Laboratory Report BNL-48937; H. Veltman, DESY Report 92-076 (1992).

2. A. Sirlin, *Phys. Rev. Lett.* **67**, 2127 (1991); *Phys. Lett.* **B267**, 240 (1991).
3. A. Sirlin, *Phys. Rev.* **D22**, 971 (1980); ibid. **D29**, 89 (1984).
4. A. Sirlin, *Phys. Lett.* **B232**, 123 (1989); S. Fanchiotti and A. Sirlin, *Phys. Rev.* **D41**, 319 (1990); G. Degrassi, S. Fanchiotti and A. Sirlin, *Nucl. Phys.* **B351**, 49 (1991).
5. P. Langacker, Lectures presented at TASI-92, Boulder, June 1992, UPR-0555T (1993).
6. P. Langacker and M. Luo, *Phys. Rev.* **D44**, 817 (1991); U. Amaldi, W. de Boer and H. Fürstman, *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, *Nuovo Cim.* **104A**, 1817 (1991); P. Langacker and N. Polonsky, UPR-0513T (1992); M. Carena, S. Pokorski and C.E.M. Wagner, MPI-Ph/93-10 (1993).
7. G.G. Ross and R.G. Roberts, *Nucl. Phys.* **B377**, 571 (1992).
8. R. Barbieri, M. Beccaria, P. Ciafaloni, G. Curci, and A. Viceré, *Phys. Lett.* **B288**, 95 (1992).
9. S. Fanchiotti, B. Kniehl and A. Sirlin, CERN-TH.6749/92, NYU-Th-92/12/05.
10. A. Djouadi and C. Verzegnassi, *Phys. Lett.* **B195**, 265 (1987), A. Djouadi, *Nuovo Cim.* **100A**, 357 (1988); B.A. Kniehl, *Nucl. Phys.* **B347**, 86 (1990).
11. B.A. Kniehl, J.H. Kühn, and R.G. Stuart, *Phys. Lett.* **B214**, 621 (1988).
12. M.J. Strassler and M.E. Peskin, *Phys. Rev.* **D43**, 1500 (1991).
13. B.A. Kniehl and A. Sirlin, *Nucl. Phys.* **B371**, 141 (1992) and *Phys. Rev.* **D47**, 883 (1993).
14. J. Fleischer, O.V. Tarasov, F. Jegerlehner and P. Rączka, BI-TP-92/31, PSI-PR-92-21 (1992); G. Degrassi, DFPD 93/TH/03 (1993); G. Buchalla and A.J. Buras, MPI-PTh 111-92, TUM-T31-36/92 (1992).
15. R. Barbieri, CERN-TH.6659/92 (1992); H.E. Haber, SCIPP 93/06 (1993); R. Barbieri, M. Frigeni, F. Giuliani and H.E. Haber, *Nucl. Phys.* **B341**, 309 (1990).
16. D. Schaile, talk given at the Ringberg Workshop on "Perspectives of the electroweak interactions in e^+e^- collisions," Ringberg, Tegernsee, Germany, April 4-8, 1993.
17. M. Peskin and T. Takeuchi, *Phys. Rev. Lett.* **65**, 964 (1990); M. Golden and L. Randall, *Nucl. Phys.* **B361**, 3 (1991); D. Kennedy and P. Langacker, *Phys. Rev. Lett.* **65**, 2967 (1990) and *Phys. Rev.* **D44**, 1591 (1991); G. Altarelli and R. Barbieri, *Phys. Lett.* **B253**, 161 (1990); B. Holdom and J. Terning, *Phys.*

Lett. **B247**, 88 (1990); B.W. Lynn, M.E. Peskin, and R.G. Stuart, in *Physics at LEP*, CERN 86-02, Vol. 1, p. 90; A. Ali and G. Degrassi, in Bég Memorial Volume, ed. by A. Ali and P. Hoodbhoy (World Scientific, Singapore, 1991), p. 70; G. Altarelli, R. Barbieri and S. Jadach, *Nucl. Phys.* **B369**, 3 (1992); J. Ellis, G.L. Fogli and E. Lisi, *Phys. Lett.* **285**, 238 (1992); G. Bhattacharyya, S. Banerjee and P. Roy, *Phys. Rev.* **D45** R729 (1992).

18. W.J. Marciano and J. Rosner, *Phys. Rev. Lett.* **65**, 2963 (1990); W.J. Marciano, *Annu. Rev. Nucl. Part. Sci.*, **41**, 469 (1991).
19. P. Langacker, private communication.
20. C.T. Hill and E.A. Paschos, *Phys. Lett.* **B241** (1990) 96.
21. S. Bertolini and A. Sirlin, *Phys. Lett.* **B257**, 179 (1991).
22. E. Gates and J. Terning, *Phys. Rev. Lett.* **67**, 1840 (1991).
23. A. Denner, R.J. Guth, and J.H. Kühn, *Phys. Lett.* **B240**, 438 (1990).
24. M. Ruderman and R. Finkelstein, *Phys. Rev.* **76**, 1458 (1949).
25. S.M. Berman, *Phys. Rev. Lett.* **1**, 468 (1958); T. Kinoshita, *Phys. Rev. Lett.* **2**, 477 (1959).
26. M.V. Terent'ev, *Yad. Fiz.* **18**, 870 (1973) [translation: *Sov. J. Nucl. Phys.* **18**, 449 (1974)].
27. W.J. Marciano and A. Sirlin, *Phys. Rev. Lett.* **36**, 1425 (1976).
28. D.I. Britton *et al.*, *Phys. Rev. Lett.* **68**, 3000 (1992).
29. G. Czapek *et al.*, *Phys. Rev. Lett.* **70**, 17 (1993).
30. D.A. Bryman, TRI-PP-93-4 (1993).
31. L. Rolandi, talk given at the XXVI ICHEP 1992, Dallas, USA, CERN-PPE/92-175 (1992).
32. A. Sirlin, *Nucl. Phys.* **B71**, 29 (1974) and *Revs. Mod. Phys.* **50**, 573 (1978).
33. For a recent review see A. Sirlin, "Universality of the Weak Interactions," to appear in "Precision Tests of the Standard Electroweak Model," Advanced Series on Directions in High Energy Physics, World Scientific Publishing Co., P. Langacker, editor.
34. M.A.B. Bég, R.V. Budny, R. Mohapatra and A. Sirlin, *Phys. Rev. Lett.* **38**, 1252 (1977); B.R. Holstein and S.B. Treiman, *Phys. Rev.* **D16**, 2369 (1977).
35. B.G. Erozolimski *et al.*, *Phys. Lett.* **B263**, 33 (1991).

Table 1. Comparison of electroweak observables and SM predictions for $m_Z = 91.187 \pm 0.007\ GeV$, $\hat{\alpha}_s(m_Z) = 0.12 \pm 0.01$, $60\ GeV < m_H < 1\ TeV$ and m_t obtained in the global fit (Eq. (10)). (From P. Langacker, Ref. [5]). The first error in the predictions arises from m_Z and Δr, the second from m_t and m_H, and the third (in brackets) from $\hat{\alpha}_s(m_Z)$. The two errors in $Q_W(Cs)$ and $\sin^2\theta_W$ are experimental and theoretical (in brackets). The value shown for $\sin^2\theta_W$ is from CCFR. Only the first eleven Z-pole observables are independent.

Quantity	Value	Standard Model
$m_Z\ (GeV)$	91.187 ± 0.007	input
$\Gamma_Z\ (GeV)$	2.491 ± 0.007	$2.490 \pm 0.001 \pm 0.005 \pm [0.006]$
$R = \Gamma_{had}/\Gamma_{l\bar{l}}$	20.87 ± 0.07	$20.78 \pm 0.01 \pm 0.01 \pm [0.07]$
$\sigma_p^h(nb)$	41.33 ± 0.18	$41.42 \pm 0.01 \pm 0.01 \pm [0.06]$
$\Gamma_{b\bar{b}}\ (MeV)$	373 ± 9	$375.9 \pm 0.2 \pm 0.5 \pm [1.3]$
$A_{FB}(\mu)$	0.0152 ± 0.0027	$0.0141 \pm 0.0005 \pm 0.0010$
$A_{pol}(\tau)$	0.140 ± 0.018	$0.137 \pm 0.002 \pm 0.005$
$A_e(P_\tau)$	0.134 ± 0.030	$0.137 \pm 0.002 \pm 0.005$
$A_{FB}(b)$	0.093 ± 0.012	$0.096 \pm 0.002 \pm 0.003$
$A_{FB}(c)$	0.072 ± 0.027	$0.068 \pm 0.001 \pm 0.003$
A_{LR}	0.100 ± 0.044	$0.137 \pm 0.002 \pm 0.005$
$\Gamma_{l\bar{l}}\ (MeV)$	83.43 ± 0.29	$83.66 \pm 0.02 \pm 0.13$
$\Gamma_{had}\ (MeV)$	1741.2 ± 6.6	$1739 \pm 1 \pm 4 \pm [6]$
$\Gamma_{inv}\ (MeV)$	499.5 ± 5.6	$500.4 \pm 0.1 \pm 0.9$
N_ν	3.004 ± 0.035	3
$\bar{g}_A$	-0.4999 ± 0.0009	-0.5
$\bar{g}_V$	-0.0351 ± 0.0025	$-0.0344 \pm 0.0006 \pm 0.0013$
$\bar{s}_W^2\ (A_{FB}(q))$	0.2329 ± 0.0031	$0.2328 \pm 0.0003 \pm 0.0007 \pm$?
$M_W\ (GeV)$	79.91 ± 0.39	$80.18 \pm 0.02 \pm 0.13$
m_W/m_Z	0.8813 ± 0.0041	$0.8793 \pm 0.0002 \pm 0.0014$
$Q_W(Cs)$	$-71.04 \pm 1.58 \pm [0.88]$	$-73.20 \pm 0.07 \pm 0.02$
$g_A^e(\nu e \to \nu e)$	-0.503 ± 0.017	$-0.505 \pm 0 \pm 0.001$
$g_V^e(\nu e \to \nu e)$	-0.025 ± 0.020	$-0.036 \pm 0.001 \pm 0.001$
$\sin^2\theta_W$	$0.2242 \pm 0.0042 \pm [0.0047]$	$0.2269 \pm 0.0003 \pm 0.0025$