PRECISION TESTS OF THE ELECTROWEAK INTERACTION *

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ABSTRACT

The status of the electroweak Standard Model is reviewed in the light of recent precision data and new theoretical results which have contributed to improve the predictions for precision observables, together with the remaining inherent theoretical uncertainties. Consequences for possible new physics are also discussed.

1. Standard Model entries:

1.1. The fermions

The family structure of the fermions is a manifestation of the SU(2)×U(1) symmetry. It has been strongly consolidated by several recent experimental informations:

Three generations of massless neutrinos: From the measurements of the Z line shape at LEP the combined LEP value for the number of light neutrinos is [1] (universal couplings assumed)

$$N_\nu = 2.987 \pm 0.017\,.$$

$m_\nu = 0$ is consistent with the experimental mass limits experiments [2]

$$m_{\nu_e} < 7.2\,\mathrm{eV}\,(95\%\,C.L.), \quad m_{\nu_\mu} < 220\,\mathrm{keV}\,(90\%\,C.L.), \quad m_{\nu_\tau} < 24\,\mathrm{MeV}\,(95\%\,C.L.)\,.$$

Universality of neutral current couplings: The vector and axial vector coupling constants of the Z to e, μ, τ measured at LEP [1] show agreement with lepton universality and with the Standard Model prediction (Figure 1).

Recent results on $\sigma(\nu_\mu e)$ and $\sigma(\bar{\nu}_\mu e)$ by the CHARM II Collaboration yield for the ν_μ and e coupling constants [3]

$$g_V^{\nu e} \equiv 2g^\nu\, g_V^e = -0.035 \pm 0.017$$
$$g_A^{\nu e} \equiv 2g^\nu\, g_A^e = -0.503 \pm 0.017,$$

compatible with $g_{V,A}^{lept}$ from LEP [1] under the assumption of lepton universality:

$$\begin{aligned} g_V^\ell &= -0.0366 \pm 0.0011 \\ g_A^\ell &= -0.50123 \pm 0.00042\,. \end{aligned}$$

*invited talk at the XV Int. Conference on Physics in Collisions, Cracow, Poland, June 1995

Figure 1: 68% C.L. contours for the leptonic coupling constants from LEP, ref (1).

Universality of charged current couplings: The τ-μ CC universality can be expressed in terms of the ratio of the effective decay constants G_τ for $\tau \to \nu_\tau e \bar{\nu}_e$ and G_μ for $\mu \to \nu_\mu e \bar{\nu}_e$ to be unity in the Standard Model:

$$\left(\frac{G_\tau}{G_\mu}\right)^2 = B_e \cdot \frac{\tau_\mu}{\tau_\tau} \left(\frac{m_\mu}{m_\tau}\right)^5 = 1\,.$$

The recent data on the τ mass m_τ, the τ lifetime τ_τ, and the branching ratio $B_e = BR(\tau \to \nu_\tau e \bar{\nu}_e)$ yield [4]

$$\left(\frac{G_\tau}{G_\mu}\right)^2 = 0.996 \pm 0.006\,, \tag{1}$$

consistent with CC τ-μ universality. The CC μ-e universality is demonstrated in terms of the experimental ratios [4]

$$\begin{aligned} B_e = BR(\tau \to \nu_\tau e \bar{\nu}_e) &= 0.1789 \pm 0.0014 \\ B_\mu = BR(\tau \to \nu_\tau \mu \bar{\nu}_\mu) &= 0.1734 \pm 0.0016\,. \end{aligned}$$

By purely kinematical reasons, $B_\mu = 0.972 B_e$, which actually is observed in the experimental ratios of Eq. (2).

The top quark: The top quark has recently been observed at the Tevatron. Its mass determination by the CDF collaboration [5] yields $m_t = 176 \pm 8 \pm 10$ GeV and by the D0 collaboration [6]: $m_t = 199^{+19}_{-21} \pm 22$ GeV, resulting in an weighted average of

$$m_t = 180 \pm 12\mathrm{GeV}\,. \tag{2}$$

1.2. The vector bosons and the Higgs sector

The spectrum of the vector bosons $\gamma, W^{\pm}, Z$ with masses [1,7]

$$M_W = 80.26 \pm 0.16\,\mathrm{GeV}, \qquad M_Z = 91.1887 \pm 0.0022\,\mathrm{GeV} \tag{3}$$

is reconciled with the SU(2)×U(1) local gauge symmetry with the help of the Higgs mechanism. For a general structure of the scalar sector, the electroweak mixing angle is related to the vector boson masses by

$$s_\theta^2 \equiv \sin^2\theta = 1 - \frac{M_W^2}{\rho M_Z^2} = 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\Delta\rho \equiv s_W^2 + c_W^2\Delta\rho \tag{4}$$

where the ρ-parameter $\rho = (1-\Delta\rho)^{-1}$ is an additional free parameter. In models with scalar doublets only, in particular in the minimal model, one has the tree level relation $\rho = 1$. Loop effects, however, induce a deviation $\Delta\rho \neq 0$.

We can get a value for ρ from directly using the data on M_W, M_Z and the mixing angle $s_\theta^2 = s_\ell^2 = 0.2318 \pm 0.0004$ measured at LEP [1] as independent experimental information, yielding $\rho = M_W^2/M_Z^2 c_\ell^2 = 1.0084 \pm 0.0041$. In the Standard Model M_W, M_Z, s_ℓ^2 are correlated. Taking into account the constraints from the data [1] yields $\rho_{SM} = 1.0066 \pm 0.0010$. The deviation $\rho - \rho_{SM}$ can be interpreted as a measure for a possibly deviating tree level structure. The present situation is consistent with the Standard Model.

2. Precision tests of the Standard Model

2.1. Loop calculations

The possibility of performing precision tests is based on the formulation of the Standard Model as a renormalizable quantum field theory preserving its predictive power beyond tree level calculations. With the experimental accuracy in the investigation of the fermion-gauge boson interactions being sensitive to the loop induced quantum effects, also the more subtle parts of the Standard Model Lagrangian are probed.

Before one can make predictions from the theory, a set of independent parameters has to be determined from experiment. All the practical schemes make use of the same physical input quantities

$$\alpha,\ G_\mu,\ M_Z,\ m_f,\ M_H \tag{5}$$

for fixing the free parameters of the SM. Differences between various schemes are formally of higher order than the one under consideration. The study of the scheme dependence of the perturbative results, after improvement by resumming the leading terms, allows us to estimate the missing higher order contributions.

Large loop effects in electroweak parameter shifts:

(i) The fermionic content of the subtracted photon vacuum polarization

$$\Delta\alpha = \Pi^{\gamma}_{ferm}(0) - \mathrm{Re}\,\Pi^{\gamma}_{ferm}(M_Z^2)$$

corresponds to a QED induced shift in the electromagnetic fine structure constant. The recent update of the evaluation of the light quark content by Eidelman and Jegerlehner [8] and Burkhardt and Pietrzyk [9] both yield the result

$$(\Delta\alpha)_{had} = 0.0280 \pm 0.0007$$

and thus confirm the previous value of [10] with an improved accuracy. Other determinations by Swartz [11] and Martin and Zeppenfeld [12] agree within one standard deviation. Together with the leptonic content, $\Delta\alpha$ can be resummed resulting in an effective fine structure constant at the Z mass scale:

$$\alpha(M_Z^2) = \frac{\alpha}{1-\Delta\alpha} = \frac{1}{128.89 \pm 0.09}\,. \tag{6}$$

(ii) The ρ-parameter in the Standard Model gets a deviation $\Delta\rho$ from 1 by radiative corrections, essentially by the contribution of the (t,b) doublet [13], in 1-loop and neglecting m_b:

$$\left[\frac{\Sigma^{ZZ}(0)}{M_Z^2} - \frac{\Sigma^{WW}(0)}{M_W^2}\right]_{(t,b)} = \frac{3G_\mu m_t^2}{8\pi^2\sqrt{2}} = \Delta\rho\,. \tag{7}$$

This potentially large contribution constitutes also the leading shift for the electroweak mixing angle when inserted into Eq. (4).

2.2. The vector boson masses

The correlation between the masses M_W, M_Z of the vector bosons in terms of the Fermi constant G_μ reads in 1-loop order of the Standard Model [14]:

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2s_W^2 M_W^2}\left[1 + \Delta r(\alpha, M_W, M_Z, M_H, m_t)\right]\,. \tag{8}$$

The 1-loop correction Δr can be written in the following way

$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\,\Delta\rho + (\Delta r)_{remainder}\,. \tag{9}$$

in order to separate the leading fermionic contributions $\Delta\alpha$ and $\Delta\rho$. All other terms are collected in the $(\Delta r)_{remainder}$, the typical size of which is of the order ~ 0.01.

The presence of large terms in Δr requires the consideration of higher than 1-loop effects. The modification of Eq. (8) according to

$$1 + \Delta r \;\rightarrow\; \frac{1}{(1-\Delta\alpha)\cdot(1+\frac{c_W^2}{s_W^2}\Delta\overline{\rho})\;-\;(\Delta r)_{remainder}} \equiv \frac{1}{1-\Delta r} \tag{10}$$

with

$$\Delta\overline{\rho} = 3\,\frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}\cdot\left[1+\frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}\rho^{(2)})+\delta\rho_{\,QCD}\right] \tag{11}$$

accommodates the following higher order terms (Δr in the denominator is an effective correction including higher orders):

- The leading log resummation [15] of $\Delta\alpha$: $1+\Delta\alpha \;\rightarrow\; (1-\Delta\alpha)^{-1}$
- The resummation of the leading m_t^2 contribution [16] in terms of $\Delta\overline{\rho}$. Thereby also irreducible higher order diagrams contribute. The electroweak 2-loop part is described by the function $\rho^{(2)}(M_H/m_t)$ derived in [17] for general Higgs masses. $\delta\rho_{\,QCD}$ is the QCD correction to the leading m_t^2 term of the ρ-parameter [18,19]

$$\delta\rho_{\,QCD} = -\,\frac{\alpha_s(\mu)}{\pi}\cdot\frac{2}{3}\left(\frac{\pi^2}{3}+1\right)+\left(\frac{\alpha_s(\mu)}{\pi}\right)^2 c_2(\mu)\,. \tag{12}$$

  with the recently calculated 3-loop coefficent [19] c_2 ($c_2 = -14.59$ for $\mu = m_t$ and 6 flavors). It reduces the scale dependence of $\delta\rho_{\,QCD}$ significantly. The complete $O(\alpha\alpha_s)$ corrections to the self energies beyond the m_t^2 approximation are available from perturbative calculations [20] and by means of dispersion relations [21]. Quite recently, also non-leading terms to Δr of $O(\alpha_s^2)$ have become available [22].

- With the quantity $(\Delta r)_{remainder}$ in the denominator non-leading higher order terms containing mass singularities of the type $\alpha^2\log(M_Z/m_f)$ from light fermions are also incorporated [23].

The quantity Δr in Eq. (10)

$$\Delta r \;=\; 1 \;-\; \frac{\pi\alpha}{\sqrt{2}G_\mu}\,\frac{1}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\,.$$

is experimentally determined by M_Z and M_W. Theoretically, it is computed from M_Z, G_μ, α after specifying the masses M_H, m_t. The theoretical prediction for Δr is displayed in Figure 2. For comparison with data, the experimental 1σ limits from the direct measurements of M_Z at LEP and M_W in $p\bar{p}$ are indicated.

The quantity s_W^2 resp. the ratio M_W/M_Z can indirectly be measured in deep-inelastic neutrino scattering, in particular in the NC/CC neutrino cross section ratio

Figure 2: Δr as a function of the top mass for $M_H = 60$ and 1000 GeV. 1σ bounds from M_Z and s_W^2: horizontal band from $p\bar{p}$, $\bullet$ from νN.

for isoscalar targets. The present world average from CCFR, CDHS and CHARM results [24]

$$s_W^2 = 0.2253 \pm 0.0047$$

is fully consistent with the direct vector boson mass measurements and with the standard theory.

1.3. Z boson observables

Measurements of the Z line shape in $e^+e^- \to f\bar{f}$

$$\sigma(s) = \sigma_0 \frac{s\Gamma_Z^2}{\mid s - M_Z^2 + i\frac{s}{M_Z^2}\Gamma_Z \mid^2} + \sigma_{\gamma Z} + \sigma_\gamma \,, \qquad \sigma_0 = \frac{12\pi}{M_Z^2} \cdot \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2} \tag{13}$$

(with small photon exchange and interference terms) yield the parameters M_Z, Γ_Z, and the partial widths Γ_f or the peak cross section σ_0. Whereas M_Z is used as a precise input parameter, together with α and G_μ, the width and partial widths allow comparisons with the predictions of the Standard Model. The predictions for the partial widths as well as for the asymmetries can conveniently be calculated in terms of effective neutral current coupling constants for the various fermions.

Effective Z boson couplings: The effective couplings follow from the set of 1-loop diagrams without virtual photons, the non-QED or weak corrections. These weak corrections can conveniently be written in terms of fermion-dependent overall normalizations ρ_f and effective mixing angles s_f^2 in the NC vertices [25]:

$$\begin{aligned} J_\nu^{NC} &= \left(\sqrt{2}G_\mu M_Z^2 \rho_f\right)^{1/2} \left[(I_3^f - 2Q_f s_f^2)\gamma_\nu - I_3^f \gamma_\nu\gamma_5\right] \\ &= \left(\sqrt{2}G_\mu M_Z^2\right)^{1/2} \left[g_V^f\,\gamma_\nu - g_A^f\,\gamma_\nu\gamma_5\right]. \end{aligned} \tag{14}$$

ρ_f and s_f^2 contain universal parts (i.e. independent of the fermion species) and non-universal parts which explicitly depend on the type of the external fermions. In their leading terms, incorporating also the next order, the parameters are given by

$$\rho_f = \frac{1}{1-\Delta\overline{\rho}} + \cdots, \quad s_f^2 = s_W^2 + c_W^2\,\Delta\overline{\rho} + \cdots \tag{15}$$

with $\Delta\overline{\rho}$ from Eq. (11).

For the b quark, also the non-universal parts have a strong dependence on m_t resulting from virtual top quarks in the vertex corrections. The difference between the d and b couplings can be parametrized in the following way

$$\rho_b = \rho_d(1+\tau)^2, \quad s_b^2 = s_d^2(1+\tau)^{-1} \tag{16}$$

with the quantity

$$\tau = \Delta\tau^{(1)} + \Delta\tau^{(2)} + \Delta\tau^{(\alpha_s)}$$

calculated perturbatively, at the present level comprising: the complete 1-loop order term [26]

$$\Delta\tau^{(1)} = -2x_t - \frac{G_\mu M_Z^2}{6\pi^2\sqrt{2}}(c_W^2+1)\log\frac{m_t}{M_W} + \cdots, \quad x_t = \frac{G_\mu m_t^2}{8\pi\sqrt{2}}; \tag{17}$$

the leading electroweak 2-loop contribution of $O(G_\mu^2 m_t^4)$ [17,27]

$$\Delta\tau^{(2)} = -2\,x_t^2\,\tau^{(2)}, \tag{18}$$

where $\tau^{(2)}$ is a function of M_H/m_t with $\tau^{(2)} = 9 - \pi^2/3$ for $M_H \ll m_t$; the QCD corrections to the leading term of $O(\alpha_s G_\mu m_t^2)$ [28]

$$\Delta\tau^{(\alpha_s)} = 2\,x_t \cdot \frac{\alpha_s}{\pi} \cdot \frac{\pi^2}{3}, \tag{19}$$

and the $O(\alpha_s)$ correction to the $\log m_t/M_W$ term in (17), with a numerically very small coefficient [29].

Asymmetries and mixing angles: The effective mixing angles are of particular interest since they determine the on-resonance asymmetries via the combinations

$$A_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}. \tag{20}$$

Measurements of the asymmetries hence are measurements of the ratios

$$g_V^f/g_A^f = 1 - 2Q_f s_f^2 \tag{21}$$

or the effective mixing angles, respectively.

Z width and partial widths: The total Z width Γ_Z can be calculated essentially as the sum over the fermionic partial decay widths

$$\Gamma_Z = \sum_f \Gamma_f + \cdots, \quad \Gamma_f = \Gamma(Z \to f\bar{f}) \tag{22}$$

The dots indicate other decay channels which, however, are not significant. The fermionic partial widths, when expressed in terms of the effective coupling constants read up to 2nd order in the (light) fermion masses:

$$\Gamma_f = \Gamma_0 \left[(g_V^f)^2 + (g_A^f)^2 \left(1 - \frac{6m_f^2}{M_Z^2} \right) \right] \cdot (1 + Q_f^2 \frac{3\alpha}{4\pi}) + \Delta\Gamma_{QCD}^f$$

with

$$\Gamma_0 = N_C^f \frac{\sqrt{2} G_\mu M_Z^3}{12\pi}, \quad N_C^f = 1 \text{ (leptons)}, \ = 3 \text{ (quarks)}.$$

The QCD correction for the light quarks with $m_q \simeq 0$ is given by

$$\Delta\Gamma_{QCD}^f = \Gamma_0 \left[(g_V^f)^2 + (g_A^f)^2 \right] \cdot K_{QCD} \tag{23}$$

with [30]

$$K_{QCD} = \frac{\alpha_s}{\pi} + 1.41 \left(\frac{\alpha_s}{\pi} \right)^2 - 12.8 \left(\frac{\alpha_s}{\pi} \right)^3 . \tag{24}$$

For b quarks the QCD corrections are different due to finite b mass terms and to top quark dependent 2-loop diagrams for the axial part:

$$\Delta\Gamma_{QCD}^b = \Delta\Gamma_{QCD}^d + \Gamma_0 \left[(g_V^b)^2 R_V + (g_A^b)^2 R_A \right] \tag{25}$$

The coefficients in the perturbative expansions

$$R_V = c_1^V \frac{\alpha_s}{\pi} + c_2^V (\frac{\alpha_s}{\pi})^2 + c_3^V (\frac{\alpha_s}{\pi})^3 + \cdots, \quad R_A = c_1^A \frac{\alpha_s}{\pi} + c_2^A (\frac{\alpha_s}{\pi})^2 + \cdots$$

depending on m_b and m_t, are calculated up to third order in the vector and up to second order in the axial part [31].

Standard Model predictions versus data: In table 1 the Standard Model predictions for Z pole observables are put together. The first error corresponds to the variation of m_t in the observed range (2) and $60 < M_H < 1000$ GeV. The second error is the hadronic uncertainty from $\alpha_s = 0.123 \pm 0.006$, as measured by QCD observables at the Z [32]. The recent combined LEP results on the Z resonance parameters [1], under the assumption of lepton universality, are also shown in table 1, together with s_e^2 from the left-right asymmetry at the SLC [33].

The value for the leptonic mixing angle from the left-right asymmetry A_{LR} has become closer to the LEP result, but due to its smaller error the deviation is still

Table 1: LEP results and Standard Model predictions for the Z parameters.

observable	LEP 1995	Standard Model prediction
M_Z (GeV)	91.1887 ± 0.0022	input
Γ_Z (GeV)	2.4971 ± 0.0032	$2.4976 \pm 0.0077 \pm 0.0033$
σ_0^{had} (nb)	41.492 ± 0.081	$41.457 \pm 0.011 \pm 0.076$
Γ_{had}/Γ_e	20.800 ± 0.035	$20.771 \pm 0.019 \pm 0.038$
Γ_{inv} (MeV)	499.5 ± 2.7	501.6 ± 1.1
Γ_b/Γ_{had}	0.2204 ± 0.0020	0.2155 ± 0.0004
Γ_c/Γ_{had}	0.1606 ± 0.0095	0.1713 ± 0.0002
ρ_ℓ	1.0049 ± 0.0017	1.0050 ± 0.0023
s_ℓ^2	0.2318 ± 0.0004	0.2317 ± 0.0012
$s_e^2(A_{LR})$	0.2305 ± 0.0005 (SLC result)	0.2317 ± 0.0012

more than 2σ. One has to keep in mind, however, that the agreement within the individually determined values for s_ℓ^2 is much better (see e.g. C. Baltay, these proceedings). Averaging the results from LEP and SLC yields

$$s_\ell^2 = 0.2313 \pm 0.0003\,.$$

A significant deviation from the Standard Model prediction is still present in the quantity $R_b = \Gamma_b/\Gamma_{had}$. The ratio R_c is not precise enough to claim a deviation from the Standard Model.

Standard Model fits: Assuming the validity of the Standard Model a global fit to all electroweak LEP results constrains the parameters m_t, α_s as follows: [1]

$$m_t = 176 \pm 10^{+17}_{-19}\,\mathrm{GeV}, \quad \alpha_s = 0.125 \pm 0.004 \pm 0.002 \tag{26}$$

with $M_H = 300$ GeV for the central value. The second error is from the variation of M_H between 60 GeV and 1 TeV. The fit results include the uncertainties of the Standard Model calculations to be discussed in the next subsection. The parameter range in Eq. (27) predicts a value for the W mass via Eq. (8,10)

$$M_W = 80.32 \pm 0.06 \pm 0.01\,\mathrm{GeV}\,,$$

in best agreement with the direct measurement, Eq. (3), but with a sizeably smaller error. Simultaneously, the result (26) is a consistency check of the QCD part of the full Standard Model : the value of α_s at the Z peak, measured from others than electroweak observables, is [32] $\alpha_s = 0.123 \pm 0.006$.

Low energy results: The measurement of the mixing angle in neutrino-e scattering by the CHARM II Collaboration yields [3]

$$\sin^2\theta_{\nu e} = 0.2324 \pm 0.0083\,. \tag{27}$$

This value coincides with the LEP result on s_ℓ^2, table 1, as expected by the theory. The major sources of a potential difference: the different scales and the neutrino charge radius, largely cancel each other by numerical coincidence [34].

The results from deep inelastic ν scattering have already been discussed in the context of M_W. Including the information from CDHS, CHARM, CCFR, and with M_W from $\bar{p}p$ modifies the fit result only marginally [1]:

$$m_t = 174 \pm 9^{+17}_{-19}\,\mathrm{GeV}, \quad \alpha_s = 0.126 \pm 0.004 \pm 0.002\,. \tag{28}$$

Incorporating the SLC result on A_{LR} yields [1]

$$m_t = 179 \pm 9^{+17}_{-19}\,\mathrm{GeV}, \quad \alpha_s = 0.125 \pm 0.004 \pm 0.002\,. \tag{29}$$

The main Higgs dependence of the electroweak predictions is only logarithmic in the Higgs mass. Hence, the sensitivity of the data to M_H is not very pronounced. Using the Tevatron value for m_t as an additional experimental constraint, the electroweak fit to all data yields $M_H < 900$ GeV with approximately 95% C.L. [1]. Similar results have been obtained in [35].

A fit to m_t leaving M_H free yields a slightly lower range [36] $m_t = 155 \pm 15$ GeV. The reason is the theoretical correlation between m_t and M_H together with the lower χ^2 values in the fits for smaller Higgs masses.

3. Status of the Standard Model predictions

For a discussion of the theoretical reliability of the Standard Model predictions one has to consider the various sources contributing to their uncertainties:

The experimental error propagating into the hadronic contribution of $\alpha(M_Z^2)$, Eq. (6), leads to $\delta M_W = 13$ MeV in the W mass prediction, and $\delta\sin^2\theta = 0.00023$ common to all of the mixing angles, which matches with the future experimental precision.

The uncertainties from the QCD contributions, besides the 3 MeV in the hadronic Z width, can essentially be traced back to those in the top quark loops for the ρ-parameter. They can be combined into the following errors [37], which have improved due to the recently available 3-loop results:

$$\delta(\Delta\rho) \simeq 1.5 \cdot 10^{-4}, \;\; \delta s_\ell^2 \simeq 0.0001$$

for $m_t = 174$ GeV, and slightly larger for heavier top.

The size of unknown higher order contributions can be estimated by different treatments of non-leading terms of higher order in the implementation of radiative corrections in electroweak observables ('options') and by investigations of the scheme dependence. Explicit comparisons between the results of 5 different computer codes based on on-shell and $\overline{MS}$ calculations for the Z resonance observables are documented in the "Electroweak Working Group Report" [38] of the recent "Reports of the Working Group on Precision Calculations for the Z Resonance" [39]. The typical size of the genuine electroweak uncertainties is of the order 0.1%. For the leptonic mixing angle, the most severe case, one finds

$$\delta s_\ell^2 \simeq 1.5 \cdot 10^{-4} \,,$$

which is again of the same order as the experimental precision. Improvements require systematic 2-loop calculations. As an example, the leptonic mixing angle is displayed in Figure 3.

Low angle Bhabha scattering for a luminosity measurement at 0.1% accuracy still requires more theoretical effort. For a description of the present status see the contributions by Jadach et al. and other authors in [39].

4. Virtual New Physics

The parametrization of the radiative corrections originating from the vector boson self-energies in terms of the static ρ-parameter $\Delta\rho(0) \equiv \epsilon_1$ and two other combinations of self-energies, ϵ_2 and ϵ_3, [40] allows a generalization of the analysis of the electroweak data which accommodates extensions of the minimal model affecting only the vector boson self-energies. There is a wide literature [41] in this field with various conventions.

Phenomenologically, the ϵ_i are parameters which can be determined experimentally from the normalization of the Z couplings and the effective mixing angle by (the residual corrections not from self-energies are dropped)

$$\rho_f = \Delta\rho(0) + M_Z^2 \Pi'^{ZZ}(M_Z^2) + \cdots, \quad s_f^2 = (1+\Delta\kappa')s_0^2 + \cdots \tag{30}$$

with s_0^2 from Eq. (26) and

$$\Delta\kappa' = -\frac{c_0^2}{c_0^2 - s_0^2}\Delta\rho(0) + \frac{\epsilon_3}{c_0^2 - s_0^2} \,, \tag{31}$$

the quantity Δr in the M_W-M_Z correlation:

$$\Delta r = \Delta\alpha - \frac{c_0^2}{s_0^2}\Delta\rho(0) + \frac{c_0^2 - s_0^2}{s_0^2}\epsilon_2 + 2\epsilon_3 \,. \tag{32}$$

The ϵ parameters have been redefined [42] into $\epsilon_{N1,N2,N3}$ by including also the v and a vertex corrections for leptons, together with a 4th quantity ϵ_b to parametrize specific non-universal left handed contributions to the Zbb vertex via

$$g_A^b = g_A^d(1+\epsilon_b), \quad g_V^b/g_A^b = (1 - \frac{4}{3}s_d^2 + \epsilon_b)\,(1+\epsilon_b)^{-1} \,. \tag{33}$$

Figure 3: 1σ contours for the ϵ parameters and the Standard Model predictions, from ref 43

Figure 3 shows the results from a global data analysis in terms of the 1σ contours. The level of consistency with the Standard Model is visualized by the Standard Model predictions displayed in terms of the lines with m_t, M_H as input quantities. The displacement of the ϵ_b-contours corresponds to the difference between the Standard Model prediction and the experimental result for R_b (see table 1). Among the alternative mechanisms of electroweak symmetry breaking, most versions of technicolor models are disfavored by the data [43,44].

Attempts to attribute the observed difference in R_b to new physics in the Zbb vertex have to obey the constraints from the other observables, in particular from $R_h = \Gamma_{had}/\Gamma_e$ and Γ_Z. In this way, a value for α_s is obtained which is about 1σ lower than the one from the Standard Model fit [45,35,46].

A current example of new physics with also extra vertex contributions is the Standard Model with two Higgs doublets. The charged Higgs bosons diminish the value of R_b even more and hence are strongly constrained, clearly disfavored for small values of $\tan\beta = v_2/v_1$ [47]. Also the neutral sector of the general 2-doublet model turns out to be severely constrained [47].

A special discussion deserves the minimal supersymmetric standard (MSSM) model as the most predictive framework beyond the minimal model. Its structure allows a similarly complete calculation of the electroweak precision observables as in the Standard Model in terms of one Higgs mass (usually taken as M_A) and $\tan\beta$, together with the set of SUSY soft breaking parameters fixing the chargino/neutralino and scalar fermion sectors. It has been known since quite some time [49,50,51,52,53,54,55,56] that light non-standard Higgs bosons as well as light stop and charginos, all around 50 GeV or little higher, yield larger values for the ratio R_b and thus diminishing the observed difference. Complete 1-loop calculations are meanwhile available for Δr [48] and for the Z boson observables [54,55,56].

In Figure 4 the range of the theoretical predictions for the various observables are displayed for the Standard Model and the MSSM ($\alpha_s = 0.123$). In the minimal model, M_H is varied as usual between 60 GeV and 1 TeV (dashed curves). The MSSM range (between the full lines) are obtained for $\tan\beta$ between 1.1 and 70, and $60 < M_A < 1000$ GeV, all other SUSY particles taken with masses obeying the present bounds from direct searches. The shaded areas denote the experimental 1σ bounds. The prefered parameter domain yielding the optimum agreement with the data comprises low values for stop, chargino and M_h, M_A, close to present lower limits. This is made more explicit by a global fit to the precision data performed in [55]. Simultaneously, α_s turns out to be closer to the world average 0.118 [46,55] (mainly from Γ_Z and R_{had}).

5. Conclusions

The agreement of the experimental high and low energy precision data with the Standard Model predictions has shown that the Standard Model works as a fully fledged quantum field theory. A great success of the Standard Model is the experimentally observed top mass range which coincides in an impressive way with the indirect determination through loop effects from precision data.

The steadily increasing accuracy of the data starts to exhibit also sensitivity to the Higgs mass, although still marginally.

Still not understood at present is the deviation from the theoretical expectation observed in the measurement of R_b. Among the possible extensions of the minimal model, supersymmetry seems to be a favorite candidate which can accomodate also a large R_b value without contradicting the other data as long as m_t is not too high and non-standard particles in the discovery range of LEP II are around.

Acknowledgement:
I want to thank G. Altarelli, A. Dabelstein, R. Ehret, M. Grünewald and D. Schaile for valuable information and helpful discussions.

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