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 \( N_\nu = 2.987 \pm 0.017 \) (universal couplings assumed)

\[
m_\nu = 0 \text{ is consistent with the experimental mass limits experiments} \text{ } \bar{m}_\nu < 7.2 \text{ eV (95\% C.L.), } m_\nu < 220 \text{ keV (90\% C.L.), } m_\tau < 24 \text{ MeV (95\% C.L.)}.
\]

Universality of neutral current couplings: The vector and axial vector coupling constants of the \( Z \) to \( e, \mu, \tau \) measured at LEP 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 \( \nu_\mu \) and \( e \) coupling constants

\[
\begin{align*}
g^e_V & \equiv 2 g^e \: g^e_V = -0.035 \pm 0.017 \\
g^{\mu e}_A & \equiv 2 g^{\mu e} \: g^A = -0.503 \pm 0.017,
\end{align*}
\]

compatible with \( g^{lept}_{V,A} \) from LEP under the assumption of lepton universality:

\[
\begin{align*}
g^e_V & = -0.0366 \pm 0.0011 \\
g^e_A & = -0.50123 \pm 0.00042.
\end{align*}
\]
Figure 1: 68% C.L. contours for the leptonic coupling constants from LEP, ref (1).

Universality of charged current couplings: The $\tau$-$\mu$ CC universality can be expressed in terms of the ratio of the effective decay constants $G_\tau$ for $\tau \to \nu_\tau e \bar{\nu}_e$ and $G_\mu$ 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 $\tau$ mass $m_\tau$, the $\tau$ lifetime $\tau_\tau$, and the branching ratio $B_e = BR(\tau \to \nu_\tau e \bar{\nu}_e)$ yield

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

consistent with CC $\tau$-$\mu$ universality. The CC $\mu$-$e$ universality is demonstrated in terms of the experimental ratios $B_\mu = 0.972 B_e$, 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 $\overline{\underline{5}}$ yields $m_t = 176 \pm 8 \pm 10$ GeV and by the D0 collaboration $\overline{\underline{6}}$: $m_t = 199^{+19}_{-21} \pm 22$ GeV, resulting in an weighted average of $m_t = 180 \pm 12$ GeV.  

$$m_t = 180 \pm 12$$  \hspace{1cm} (2)
1.2. The vector bosons and the Higgs sector

The spectrum of the vector bosons $\gamma, W^\pm, Z$ with masses

$$M_W = 80.26 \pm 0.16 \text{ GeV}, \quad M_Z = 91.1887 \pm 0.0022 \text{ GeV}$$

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

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

where the $\rho$-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 $\rho$ from directly using the data on $M_W, M_Z$ and the mixing angle $s_\theta^2 = s^2_\ell = 0.2318 \pm 0.0004$ measured at LEP as independent experimental information, yielding $\rho = M_W^2 / M_Z^2 c_\ell^2 = 1.0084 \pm 0.0041$. In the Standard Model $M_W, M_Z, s_\ell^2$ are correlated. Taking into account the constraints from the data 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

$$\alpha, G_\mu, M_Z, m_f, M_H$$

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
\[
\Delta \alpha = \Pi^\gamma_{\text{ferm}}(0) - \text{Re} \Pi^\gamma_{\text{ferm}}(M^2_Z)
\]
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
\[
(\Delta \alpha)_{\text{had}} = 0.0280 \pm 0.0007
\]
and thus confirm the previous value of \(^8\) 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:
\[
\alpha(M^2_Z) = \frac{\alpha}{1 - \Delta \alpha} = \frac{1}{128.89 \pm 0.09}.
\]

(ii) The \(\rho\)-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 \(m_b\):
\[
\left[ \frac{\Sigma_{ZZ}(0)}{M^2_Z} - \frac{\Sigma_{WW}(0)}{M^2_W} \right]_{(t,b)} = \frac{3G_\mu m_t^2}{8\pi^2\sqrt{2}} = \Delta \rho.
\]
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 \(G_\mu\) reads in 1-loop order of the Standard Model \(^14\):
\[
\frac{G_\mu}{\sqrt{2}} = \frac{\pi \alpha}{2s_W^2 M^2_W} [1 + \Delta r(\alpha, M_W, M_Z, M_H, m_t)].
\]
The 1-loop correction \(\Delta r\) can be written in the following way
\[
\Delta r = \Delta \alpha - \frac{c^2_W}{s^2_W} \Delta \rho + (\Delta r)_{\text{remainder}}.
\]
in order to separate the leading fermionic contributions \(\Delta \alpha\) and \(\Delta \rho\). All other terms are collected in the \((\Delta r)_{\text{remainder}}\), the typical size of which is of the order \(\sim 0.01\).
The presence of large terms in $\Delta r$ requires the consideration of higher than 1-loop effects. The modification of Eq. (8) according to

$$1 + \Delta r \rightarrow \frac{1}{(1 - \Delta \alpha) \cdot (1 + \frac{\pi^2}{8N_c \Delta \varphi} - \Delta r)_{\text{remainder}}} \equiv \frac{1}{1 - \Delta r} \quad (10)$$

with

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

accommodates the following higher order terms ($\Delta r$ in the denominator is an effective correction including higher orders):

- The leading log resummation \(^{13}\) of $\Delta \alpha$: $1 + \Delta \alpha \rightarrow (1 - \Delta \alpha)^{-1}$

- The resummation of the leading $m_t^2$ contribution \(^{14}\) in terms of $\Delta \varphi$. 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, $\delta \rho_{\text{QCD}}$ is the QCD correction to the leading $m_t^2$ term of the $\rho$-parameter \(^{18,19}\)

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

with the recently calculated 3-loop coefficient \(^{19}\) $c_2$ ($c_2 = -14.59$ for $\mu = m_t$ and 6 flavors). It reduces the scale dependence of $\delta \rho_{\text{QCD}}$ significantly. The complete $O(\alpha_s)$ 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 $\Delta r$ of $O(\alpha_s^2)$ have become available \(^{22}\).

- With the quantity $(\Delta r)_{\text{remainder}}$ 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 $\Delta r$ 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 $M_Z, G_\mu, \alpha$ after specifying the masses $M_H, m_t$. The theoretical prediction for $\Delta r$ is displayed in Figure 2. For comparison with data, the experimental 1$\sigma$ limits from the direct measurements of $M_Z$ at LEP and $M_W$ in $p\bar{p}$ are indicated.

The quantity $s_{\text{EW}}^2$ 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: $\Delta r$ 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 $p\bar{p}$, • from $\nu N$.

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

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

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 $e^+e^- \rightarrow f\bar{f}$

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

(with small photon exchange and interference terms) yield the parameters $M_Z$, $\Gamma_Z$, and the partial widths $\Gamma_f$ or the peak cross section $\sigma_0$. Whereas $M_Z$ is used as a precise input parameter, together with $\alpha$ and $G_\mu$, 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 nor-
malizations $\rho_f$ and effective mixing angles $s_f^2$ in the NC vertices:

$$J_{\nu}^{NC} = \left(\sqrt{2}G_\mu M_Z^2 \rho_f\right)^{1/2} \left[I_3^f - 2Q_fs_f^2\gamma_\nu - I_3^f\gamma_\nu\gamma_5\right]$$

$$= \left(\sqrt{2}G_\mu M_Z^2\right)^{1/2} \left[g_V^f\gamma_\nu - g_A^f\gamma_\nu\gamma_5\right]. \quad (14)$$

$\rho_f$ 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

$$\rho_f = \frac{1}{1 - \Delta \rho} + \cdots, \quad s_f^2 = s_W^2 + c_W \Delta \vec{\tau} + \cdots \quad (15)$$

with $\Delta \vec{\tau}$ 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

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

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

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

the leading electroweak 2-loop contribution of $O(G_\mu^2 m_t^4)$

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

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 $O(\alpha_s G_\mu m_t^2)$

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

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

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

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

Measurements of the asymmetries hence are measurements of the ratios

$$g_V^f/g_A^f = 1 - 2Q_fs_f^2 \quad (21)$$
or the effective mixing angles, respectively.
**Z width and partial widths:** The total Z width $\Gamma_Z$ can be calculated essentially as the sum over the fermionic partial decay widths

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

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:

$$\Gamma_f = \Gamma_0 \left[ (g_V f)^2 + (g_A f)^2 \right] \cdot (1 + Q^2 f 3\alpha s / 4\pi) + \Delta \Gamma_{QCD}^f$$

with

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

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

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

with

$$K_{QCD} = \frac{\alpha_s}{\pi} + 1.41 \left( \frac{\alpha_s}{\pi} \right)^2 - 12.8 \left( \frac{\alpha_s}{\pi} \right)^3.$$  \hspace{1cm} (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:

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

The coefficients in the perturbative expansions

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

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.

**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. The recent combined LEP results on the Z resonance parameters, under the assumption of lepton universality, are also shown in table 1, together with $s^2_e$ from the left-right asymmetry at the SLC.

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)| $91.1887 \pm 0.0022$| $91.1887 \pm 0.0022$ input |
| $\Gamma_Z$ (GeV) | $2.4971 \pm 0.0032$| $2.4976 \pm 0.0077 \pm 0.0033$ |
| $\sigma_0^{had}$ (nb) | $41.492 \pm 0.081$| $41.457 \pm 0.011 \pm 0.076$ |
| $\Gamma_{had}/\Gamma_e$ | $20.800 \pm 0.035$| $20.771 \pm 0.019 \pm 0.038$ |
| $\Gamma_{inv}$ (MeV) | $499.5 \pm 2.7$| $501.6 \pm 1.1$ |
| $\Gamma_b/\Gamma_{had}$ | $0.2204 \pm 0.0020$| $0.2155 \pm 0.0004$ |
| $\Gamma_c/\Gamma_{had}$ | $0.1606 \pm 0.0095$| $0.1713 \pm 0.0002$ |
| $\rho_\ell$ | $1.0049 \pm 0.0017$| $1.0050 \pm 0.0023$ |
| $s_\ell^2$ | $0.2318 \pm 0.0004$| $0.2317 \pm 0.0012$ |
| $s_\ell^2 (A_{LR})$ | $0.2305 \pm 0.0005$| $0.2317 \pm 0.0012$ (SLC result) |

more than $2\sigma$. One has to keep in mind, however, that the agreement within the individually determined values for $s_\ell^2$ 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 $m_t, \alpha_s$ as follows:

$$m_t = 176 \pm 10^{+15}_{-19} \text{ GeV}, \quad \alpha_s = 0.125 \pm 0.004 \pm 0.002$$  \hspace{1cm} (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)

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

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 $\alpha_s$ at the $Z$ peak, measured from others than electroweak observables, is $\alpha_s = 0.123 \pm 0.006$. 


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

\[ \sin^2 \theta_{\nu e} = 0.2324 \pm 0.0083. \]  

This value coincides with the LEP result on $s^2_{\ell}$, 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.

The results from deep inelastic $\nu$ 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.

\[ m_t = 174 \pm 9_{-19}^{+17} \text{GeV}, \quad \alpha_s = 0.126 \pm 0.004 \pm 0.002. \]  

Incorporating the SLC result on $A_{LR}$ yields

\[ m_t = 179 \pm 9_{-19}^{+17} \text{GeV}, \quad \alpha_s = 0.125 \pm 0.004 \pm 0.002. \]  

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.

A fit to $m_t$ leaving $M_H$ free yields a slightly lower range $m_t = 155 \pm 15$ GeV. The reason is the theoretical correlation between $m_t$ and $M_H$ together with the lower $\chi^2$ 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 $\rho$-parameter. They can be combined into the following errors, which have improved due to the recently available 3-loop results:

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

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 $\rho$-parameter $\Delta \rho(0) \equiv \epsilon_1$ and two other combinations of self-energies, $\epsilon_2$ and $\epsilon_3$, [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 $\epsilon_i$ 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)

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

with $s_0^2$ from Eq. (26) and

$$\Delta \kappa' = -\frac{\epsilon_0^2}{c_0^2 - s_0^2} \Delta \rho(0) + \frac{\epsilon_3}{c_0^2 - s_0^2},$$

the quantity $\Delta r$ in the $M_W - M_Z$ correlation:

$$\Delta r = \Delta \alpha - \frac{\epsilon_0^2}{s_0^2} \Delta \rho(0) + \frac{s_0^2 - s_0^2}{s_0^2} \epsilon_2 + 2 \epsilon_3.$$  

The $\epsilon$ 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 $\epsilon_b$ to parametrize specific non-universal left handed contributions to the $Zbb$ vertex via

$$g_A^b = g_A^d (1 + \epsilon_b), \quad g_V^b / g_A^b = (1 - \frac{4}{3} s_d^2 + \epsilon_b) (1 + \epsilon_b)^{-1}. (33)$$
Figure 3: 1σ contours for the $\epsilon$ 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 $\epsilon_b$-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.

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 $R_h = \Gamma_{\text{had}}/\Gamma_e$ and $\Gamma_Z$. In this way, a value for $\alpha_s$ is obtained which is about 1σ lower than the one from the Standard Model fit.

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 $\tan \beta = v_2/v_1$. Also the neutral sector of the general 2-doublet
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 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 $\Delta r$ and for the $Z$ boson observables.

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 [43]. Simultaneously, $\alpha_s$ turns out to be closer to the world average 0.118 [44] (mainly from $\Gamma_Z$ 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. Grünwald and D. Schaile for valuable information and helpful discussions.
6. References

1. LEP preliminary data, Rencontre de Moriond 1995; The LEP Electroweak Working Group, internal note LEPEWWG/51-01 (1995)
2. A. Smirnov, proceedings of the XVI International Symposium on Lepton and Photon Interactions, Cornell University, Ithaca 1993, eds.: P. Drell and D. Rubin; ALEPH Collaboration, D. Buskulic et al., Phys. Lett. B 349 (1995) 585
3. CHARM II Collaboration, P. Vilain et al., Phys. Lett. B 335 (1994) 246
4. A. Schwarz, proceedings of the XVI International Symposium on Lepton and Photon Interactions, Cornell University, Ithaca 1993, eds.: P. Drell and D. Rubin
5. CDF Collaboration, F. Abe et al., FERMILAB-PUB-95/022-E (1995)
6. D0 Collaboration, S. Abachi et al., FERMILAB-PUB-95/028-E (1995)
7. UA2 Collaboration, J. Alitti et al., Phys. Lett. B 276 (1992) 354; CDF Collaboration, F. Abe et al., Phys. Rev. D 43 (1991) 2070; D0 Collaboration, C.K. Jung, talk at the 27th International Conference on High Energy Physics, Glasgow 1994; CDF Collaboration, F. Abe et al., FERMILAB-PUB-95/033-E; FERMILAB-PUB-95/035-E (1995)
8. S. Eidelman, F. Jegerlehner, preprint PSI-PR-95-1/BUDKERINP 95-5 (1995)
9. H. Burkhardt, B. Pietrzyk, preprint LAPP-EXP-95.05 (1995)
10. F. Jegerlehner, Progress in Particle and Nuclear Physics 27 (1991) 1, updated from: H. Burkhardt, F. Jegerlehner, G. Penso, C. Verzegnassi, Z. Phys. C 43 (1989) 497;
11. M.L. Swartz, preprint SLAC-PUB-6710 (1994), revised version
12. A.D. Martin, D. Zeppenfeld, preprint MAD/PH/855 (1995)
13. M. Veltman, Nucl. Phys. B 123 (1977) 89; M.S. Chanowitz, M.A. Furman, I. Hinchliffe, Phys. Lett. B 78 (1978) 285
14. A. Sirlin, Phys. Rev. 22 (1980) 971; W.J. Marciano, A. Sirlin, Phys. Rev. 22 (1980) 2695
15. W.J. Marciano, Phys. Rev. D 20 (1979) 274
16. M. Consoli, W. Hollik, F. Jegerlehner, Phys. Lett. B 227 (1989) 167
17. R. Barbieri, M. Beccaria, P. Ciafaloni, G. Curci, A. Vicere, Phys. Lett. B 288 (1992) 95; Nucl. Phys. B 409 (1993) 105; J. Fleischer, F. Jegerlehner, O.V. Tarasov, Phys. Lett. B 319 (1993) 249
18. A. Djouadi, C. Verzegnassi, Phys. Lett. B 195 (1987) 265
19. L. Avdeev, J. Fleischer, S. Mikhailov, O. Tarasov, Bielefeld preprint BI-TH-93/60 (revised version); K.G. Chetyrkin, J.H. Kühn, M. Steinhauser, Phys. Lett. B 351 (1995) 331
20. A. Djouadi, Nuovo Cim. A 100 (1988) 357; D. Yu. Bardin, A.V. Chizhov, Dubna preprint E2-89-525 (1989); B.A. Kniehl, Nucl. Phys. B 347 (1990) 86; F. Halzen, B.A. Kniehl, Nucl. Phys. B 353 (1991) 567; A. Djouadi, P. Gambino, Phys. Rev. D 49 (1994) 3499
21. B.A. Kniehl, J.H. Kühn, R.G. Stuart, Phys. Lett. B 214 (1988) 621; B.A. Kniehl, A. Sirlin, Nucl. Phys. B 371 (1992) 141; Phys. Rev. D 47 (1993) 883; S. Fanchiotti, B.A. Kniehl, A. Sirlin, Phys. Rev. D 48 (1993) 307
22. K.G. Chetyrkin, J.H. Kühn, M. Steinhauser, preprint KA-TTP95-13
23. A. Sirlin, Phys. Rev. D 29 (1984) 89
24. CDHS Collaboration, H. Abramowicz et al., Phys. Rev. Lett. 57 (1986) 298; A. Blondel et al, Z. Phys. C 45 (1990) 361; CHARM Collaboration, J.V. Allaby et al., Phys. Lett. B 177 (1987) 446; Z. Phys. C 36 (1987) 611; CHARM-II Collaboration, D. Geiregat et al., Phys. Lett. B 247 (1990) 131; Phys. Lett. B 259 (1991) 499; CCFR Collaboration, C.G. Arroyo et al., Phys. Rev. Lett. 72 (1994) 3452
25. D. Bardin, M.S. Bilenky, G.V. Mithelmakher, T. Riemann, M. Sachwitz, Z. Phys. C 44 (1989) 493; W. Hollik, Munich preprints MPI-Ph/93-21, MPI-Ph/93-22 (1993), in: Precision tests of the Standard Model, ed. P. Langacker, World Scientific, Singapore 1995
26. A.A. Akhundov, D.Yu. Bardin, T. Riemann, Nucl. Phys. B 276 (1986) 1; W. Beenakker, W. Hollik, Z. Phys. C 40 (1988) 141; J. Bernabeu, A. Pich, A. Santamaria, Phys. Lett. B 200 (1988) 569;
27. A. Denner, W. Hollik, B. Lampe, Z. Phys. C 60 (1993) 193
28. J. Fleischer, F. Jegerlehner, P. Rączka, O.V. Tarasov, Phys. Lett. B 293 (1992) 437; G. Buchalla, A.J. Buras, Nucl. Phys. B 398 (1993) 285; G. Degrassi, Nucl. Phys. B 407 (1993) 271; K.G. Chetyrkin, A. Kwiatkowski, M. Steinhauser, Mod. Phys. Lett. A 8 (1993) 2785
29. A. Kwiatkowski, M. Steinhauser, Phys. Lett. B 344 (1995) 359; S. Peris, A. Santamaria, CERN-TU-R-95-21 (1995)
30. K.G. Chetyrkin, A.L. Kataev, F.V. Tkachov, Phys. Lett. B 85 (1979) 277; M. Dine, J. Sapirstein, Phys. Rev. Lett. 43 (1979) 668; W. Celmaster, R. Gonsalves, Phys. Rev. Lett. 44 (1980) 560; S.G. Gorishny, A.L. Kataev, S.A. Larin, Phys. Lett. B 259 (1991) 144; L.R. Surguladze, M.A. Samuel, Phys. Rev. Lett. 66 (1991) 560
31. T.H. Chang, K.J.F Gaemers, W.L. van Neerven, Nucl. Phys. B 202 (1982) 407; J.H. Kühn, B.A. Kniehl, Phys. Lett. B 224 (1990) 229; Nucl. Phys. B 329 (1990) 547; K.G. Chetyrkin, J.H. Kühn, Phys. Lett. B 248 (1992) 359; K.G. Chetyrkin, J.H. Kühn, A. Kwiatkowski, Phys. Lett. B 282 (1992) 221; K.G. Chetyrkin, A. Kwiatkowski, Phys. Lett. B 305 (1993) 285; Karlsruhe preprint TTP93-24 (1993); K.G. Chetyrkin, Karlsruhe preprint TTP93-5 (1993); K.G. Chetyrkin, J.H. Kühn, A. Kwiatkowski, in [39], p. 175; S. Larin, T. van Ritbergen, J.A.M. Vermaseren, ibidem, p. 265
32. S. Bethke, talk at the Tennessee International Symposium on Radiative Corrections, Gatlinburg 1994, to appear in the Proceedings
33. SLD Collaboration, K. Abe et al., Phys. Rev. Lett. 73 (1994) 25.
For the new value see: C. Baltay, these proceedings
34. S. Sarantakos, A. Sirlin, Nucl. Phys. B 217 (1983) 84; D.Yu. Bardin V.A. Dokuchaeva, Nucl. Phys. B 246 (1984) 221; M. Böhm, W. Hollik, H. Spiesberger, Z. Phys. C 27 (1985) 523
35. P.Chankowski, S. Pokorski, preprint MPI-Ph/95-39
36. J. Ellis, G.L. Fogli, E. Lisi, CERN-TH.7261/94 (updated)
37. B.A. Kniehl, in [39], p. 299
38. D. Bardin et al., in [39], p. 7
39. Reports of the Working Group on Precision Calculations for the Z Resonance,
CERN 95-03 (1995), eds. D. Bardin, W. Hollik, G. Passarino

40. G. Altarelli, R. Barbieri, Phys. Lett. B 253 (1991) 161; G. Altarelli, R. Barbieri, S. Jadach, Nucl. Phys. B 269 (1992) 3; E. Nucl. Phys. B 276 (1992) 444

41. M.E. Peskin, T. Takeuchi, Phys. Rev. Lett. 65 (1990) 964; W.J. Marciano, J.L. Rosner, Phys. Rev. Lett. 65 (1990) 2963; B.W. Lynn, M.E. Peskin, R.G. Stuart, in: Physics with LEP, eds. J. Ellis and R. Peccei, CERN 86-02 (1986); D.C. Kennedy, P. Langacker, Phys. Rev. Lett. 65 (1990) 2967; R. Barbieri, M. Frigeni, F. Caravaglios, Phys. Lett. B 279 (1992) 169; V.A. Novikov, L.B. Okun, M.I. Vysotsky, CERN-TH.6943/93 (1993), M. Bilenky, K. Kolodziej, M. Kuroda, D. Schildknecht, Phys. Lett. B 319 (1993) 319

42. G. Altarelli, R. Barbieri, F. Caravaglios, Nucl. Phys. B 405 (1993) 3; CERN-TH.6895/93 (1993)

43. G. Altarelli, updated from ref [42] (private communication)

44. B. Holdom, J. Terning, Phys. Lett. B 247 (1990) 88; M. Golden, L. Randall, Nucl. Phys. B 361 (1991) 3; C. Roiesnel, T.N. Truong, Phys. Lett. B 256 (1991) 439; T. Appelquist, G. Triantaphyllou, Phys. Lett. B 278 (1992) 345; J. Ellis, G.L. Fogli, E. Lisi, Phys. Lett. B 285 (1992) 238; CERN-TH.7448/94 (1994); S. Chivukula, proceedings of the XVI International Symposium on Lepton and Photon Interactions, Cornell University, Ithaca 1993, eds.: P. Drell and D. Rubin

45. D. Schildknecht, preprint BI-TP 95/09 (1995)

46. D. Garcia, J. Solà, preprint UAB-FT-365 (1995)

47. F. Cornet, W. Hollik, W. Möslle, Nucl. Phys. B 428 (1994) 61

48. P. Chankowski, A. Dabelstein, W. Hollik, W. Möslle, S. Pokorski, J. Rosiek, Nucl. Phys. B 417 (1994) 101; D. Garcia, J. Solà, Mod. Phys. Lett. A 9 (1994) 211

49. A. Denner, R. Guth, W. Hollik, J.H. Kühn, Z. Phys. C 51 (1991) 695

50. M. Boulware, D. Finnell, Phys. Rev. D 44 (1991) 2054

51. G. Altarelli, R. Barbieri, F. Caravaglios, CERN-TH.7536/94 (1994)

52. C.S. Lee, B.Q. Hu, J.H. Yang, Z.Y. Fang, J. Phys. G 19 (1993) 13; Q. Hu, J.M. Yang, C.S. Li, Comm. Theor. Phys. 20 (1993) 213

53. J.D. Wells, C. Kolda, G.L. Kane, Phys. Lett. B 338 (1994) 219; G.L. Kane, R.G. Stuart, J.D. Wells, preprint UM-TH-95-16 (1995)

54. D. Garcia, R. Jiménez, J. Solà, preprints UAB-FT-343, UAB-FT-344 (1994) and UAB-FT-358 (1995)

55. P. Chankowski, S. Pokorski, preprint IFT-95/5 (1995)

56. A. Dabelstein, W. Hollik, W. Möslle, preprint KA-TP-5-1995 (1995), to appear in the Proceedings of the Ringberg Workshop “Perspectives for the Electroweak Interaction”, Ringberg Castle, February 1995