TESTS OF THE STANDARD MODEL

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In this conference report a summary is given on the recent theoretical work that has contributed to improve the theoretical predictions for testing the standard model in present and future experiments. Precision calculations for the Z resonance are reviewed and the status of the standard model is discussed in the light of the recent top discovery and of the results from precision experiments. Furthermore, theoretical progress for the Higgs search, for W physics at LEP II, and for the anomalous magnetic moment of the muon is summarized. New Physics beyond the minimal model is briefly discussed, in particular the mimimal supersymmetric standard model in view of the recent electroweak precision data.

1 Introduction

The present generation of high precision experiments imposes stringent tests on the standard model of electroweak and strong interactions [1]. Besides the impressive achievements in the determination of the Z boson parameters [1,2] and the W mass [3], the most important step has been the confirmation of the top quark at the Tevatron [4,5,6]. Its mass determination by the CDF collaboration [4] yields $m_t = 176 \pm 8 \pm 10$ GeV and by the D0 collaboration [5]: $m_t = 199^{+19}_{-21} \pm 22$ GeV, resulting in an weighted average of

$$m_t = 180 \pm 12\text{GeV}\,. \tag{1}$$

The high experimental sensitivity in the electroweak observables, at the level of quantum effects, requires the highest standards on the theoretical side as well. A sizeable amount of work has contributed over the last few years to a steadily rising improvement of the standard model predictions pinning down the theoretical uncertainties to a level sufficiently small for the current interpretation of the precision data, but still sizeable enough to provoke conflict with a further increase in the experimental accuracy.

In this report we review the recent theoretical work which has provided the current theoretical basis for tests of the standard model at present and future colliders. A detailed description of the standard model predictions for observables around the Z peak can be found in the Working Group report on 'Precision Calculations for the Z Resonance' [7] (see also the talk by Bardin at this conference [8]). This is followed by a discussion of the present status of the standard model in the light of the recent experimental results. Afterwards we report on theoretical progress in the study of Higgs and WW physics, and for g-2 for muons. A short discussion of the status of the MSSM concludes this presentation.

2 Theory for precision tests

2.1 Radiative corrections

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. The higher order terms induce the sensitivity of electroweak observables to the top and Higgs mass m_t, M_H and to the strong coupling constant α_s.

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

$$\alpha,\ G_\mu,\ M_Z,\ m_f,\ M_H;\ \alpha_s \tag{2}$$

for fixing the free parameters of the standard model. 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.

Two fermion induced large loop effects in electroweak observables deserve a special discussion:

- The light 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, Jegerlehner [9] and Burkhardt, Pietrzyk [10] both yield the result

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

and thus confirm the previous value of [11] with an improved accuracy. Other determinations [12,13] 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:

$$\alpha(M_Z^2) = \frac{\alpha}{1-\Delta\alpha} = \frac{1}{128.89 \pm 0.09}. \quad (3)$$

- For a general structure of the scalar sector, the electroweak mixing angle is related to the vector boson masses by

$$\begin{aligned}\sin^2\theta &= 1 - \frac{M_W^2}{\rho M_Z^2} = 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\Delta\rho \\ &\equiv s_W^2 + c_W^2\,\Delta\rho \end{aligned} \quad (4)$$

where the ρ-parameter $\rho = (1-\Delta\rho)^{-1}$ is an additional free parameter. In the standard model, one has the tree level relation $\rho = 1$. Loop effects, however, induce a deviation $\Delta\rho \neq 0$. The main contribution is from the (t,b) doublet [14], in 1-loop and neglecting m_b given by:

$$\Delta\rho^{(1)} = 3x_t, \quad x_t = \frac{G_\mu m_t^2}{8\pi^2\sqrt{2}} \quad (5)$$

Higher order irreducible contributions have become available, modifying $\Delta\rho$ according to

$$\Delta\rho = 3x_t \cdot [1 + x_t\,\rho^{(2)} + \delta\rho_{\,QCD}] \quad (6)$$

The electroweak 2-loop part [15,16] is described by the function $\rho^{(2)}(M_H/m_t)$ derived in [16] for general Higgs masses. $\delta\rho_{\,QCD}$ is the QCD correction to the leading $G_\mu m_t^2$ term [17,18]

$$\delta\rho_{\,QCD} = -\frac{\alpha_s(\mu)}{\pi}c_1 + \left(\frac{\alpha_s(\mu)}{\pi}\right)^2 c_2(\mu) \quad (7)$$

with

$$c_1 = \frac{2}{3}\left(\frac{\pi^2}{3}+1\right) \quad (8)$$

and the recently calculated 3-loop coefficent [18]

$$c_2 = -14.59 \text{ for } \mu = m_t \text{ and 6 flavors} \quad (9)$$

with the on-shell top mass m_t. It reduces the scale dependence of $\delta\rho_{\,QCD}$ significantly and hence is an important entry to decrease the theoretical uncertainty of the standard model predictions for precision observables (see section 2.4).

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, in 1-loop order given by [19]:

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2 s_W^2 M_W^2}[1 + \Delta r(\alpha, M_W, M_Z, M_H, m_t)]. \quad (10)$$

The decomposition

$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\,\Delta\rho^{(1)} + (\Delta r)_{remainder}. \quad (11)$$

separates 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. (10) according to

$$\begin{aligned} 1 + \Delta r \quad &\rightarrow \quad \frac{1}{(1-\Delta\alpha)\cdot(1+\frac{c_W^2}{s_W^2}\Delta\rho) \;-\; (\Delta r)_{remainder}} \\ &\equiv \quad \frac{1}{1-\Delta r} \end{aligned} \quad (12)$$

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

- The leading log resummation [20] of $\Delta\alpha$: $1+\Delta\alpha \rightarrow (1-\Delta\alpha)^{-1}$
- The resummation of the leading m_t^2 contribution [21] in terms of $\Delta\rho$ in Eq. (6). Beyond the $G_\mu m_t^2 \alpha_s$ approximation through the ρ-parameter, the complete $O(\alpha\alpha_s)$ corrections to the self energies are available from perturbative calculations [22] and by means of dispersion relations [23]. All the higher order terms contribute with the same positive sign to Δr, thus making the top mass dependence of Δr significantly flatter. This is of high importance for the determination of an upper bound on m_t from M_W measurements, which is affected by the order of 10 GeV. Quite recently, also non-leading terms to Δr of the type

$$\Delta r_{(bt)} = 3x_t\left(\frac{\alpha_s}{\pi}\right)^2\left(a_1\frac{M_Z^2}{m_t^2} + a_2\frac{M_Z^4}{m_t^4}\right)$$

have been computed [24]. For $m_t = 180$ GeV they contribute an extra term of $+0.0001$ to Δr and thus are within the uncertainty from $\Delta\alpha$.

- 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 [25].

2.3 Z boson observables

Measurements of the Z line shape in $e^+e^- \to f\bar{f}$ yield the parameters M_Z, Γ_Z, and the partial widths Γ_f or the peak cross section

$$\sigma_0^f = \frac{12\pi}{M_Z^2} \cdot \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2}. \qquad (13)$$

Whereas M_Z is used as a precise input parameter, together with α and G_μ, the width, partial widths and asymmetries 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 [26]:

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

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

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

with $\Delta\rho$ from Eq. (6).

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

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

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 [27] with x_t from Eq. (5):

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

the leading electroweak 2-loop contribution of $O(G_\mu^2 m_t^4)$ [16,28]

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

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 $O(\alpha_s G_\mu m_t^2)$ [29]

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

and the $O(\alpha_s)$ correction to the $\log m_t/M_W$ term in (17), with a numerically very small coefficient [30].

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

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

Measurements of the asymmetries hence are measurements of the ratios

$$g_V^f/g_A^f = 1 - 2Q_f s_f^2 \qquad (21)$$

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

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

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:

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

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

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

with [31]

$$K_{QCD} = \frac{\alpha_s}{\pi} + 1.41\left(\frac{\alpha_s}{\pi}\right)^2 - 12.8\left(\frac{\alpha_s}{\pi}\right)^3 - \frac{Q_f^2}{4}\frac{\alpha\alpha_s}{\pi^2}.$$

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:

$$\Delta\Gamma_{QCD}^b = \Delta\Gamma_{QCD}^d + \Gamma_0\left[(g_V^b)^2 R_V + (g_A^b)^2 R_A\right] \qquad (24)$$

The coefficients in the perturbative expansions

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

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 [32].

Radiation of secondary fermions through photons from the primary final state fermions can yield another sizeable contribution to the partial Z widths which, however, is compensated by the corresponding virtual contribution through the dressed photon propagator in the final state vertex correction. For this compensation it is essential that the analysis is inclusive enough, i.e. the cut to the invariant mass of the secondary fermions is sufficiently large [33].

2.4 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. (3), 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 [34], which have improved due to the recently available 3-loop result:

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

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" [35] in ref. [7] (see also the talk by Bardin [8]). The typical size of the genuine electroweak uncertainties is of the order 0.1%. The following table shows the uncertainty in a selected set of precision observables. In particular for the very precise s_e^2 the theoretical uncertainty is still remarkable. Improvements of the accuracy displayed in table 1 require systematic electroweak and QCD-electroweak 2-loop calculations. As an example for the importance of electroweak non-leading 2-loop effects, an explicit calculation of these terms has been performed for ρ (the overall normalization) in neutrino scattering [36]: they are sizeable and comparable to the $O(G_\mu^2 m_t^4)$ term. Hence, one should take the registered uncertainties also for the Z region very seriously.

Table 1: Largest half-differences among central values (Δ_c) and among maximal and minimal predictions (Δ_g) for $m_t = 175$ GeV, $60\,\text{GeV} < M_H < 1\,\text{TeV}$ and $\alpha_s(M_Z^2) = 0.125$ (from ref. [35])

Observable O	$\Delta_c O$	$\Delta_g O$
M_W (GeV)	4.5×10^{-3}	1.6×10^{-2}
Γ_e (MeV)	1.3×10^{-2}	3.1×10^{-2}
Γ_Z (MeV)	0.2	1.4
s_e^2	5.5×10^{-5}	1.4×10^{-4}
s_b^2	5.0×10^{-5}	1.5×10^{-4}
R_{had}	4.0×10^{-3}	9.0×10^{-3}
R_b	6.5×10^{-5}	1.7×10^{-4}
R_c	2.0×10^{-5}	4.5×10^{-5}
σ_0^{had} (nb)	7.0×10^{-3}	8.5×10^{-3}
A_{FB}^l	9.3×10^{-5}	2.2×10^{-4}
A_{FB}^b	3.0×10^{-4}	7.4×10^{-4}
A_{FB}^c	2.3×10^{-4}	5.7×10^{-4}
A_{LR}	4.2×10^{-4}	8.7×10^{-4}

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 [7]. Presently an accuracy of 0.16% has been claimed [37].

3 Standard model predictions versus data

In table 2 the standard model predictions for Z pole observables and the W mass are put together. The first error corresponds to the variation of m_t in the observed range (1) 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 [39]. The recent combined LEP results [1] on the Z resonance parameters, 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 [40,1].

The value for the leptonic mixing angle from the left-right asymmetry A_{LR} has come closer to the LEP result, but due to its smaller error the deviation from the cumulative LEP average is still 3σ.

Significant deviations from the standard model predictions are observed in the ratios $R_b = \Gamma_b/\Gamma_{had}$ and $R_c = \Gamma_c/\Gamma_{had}$. The experimental values, together with the top mass (1) from the Tevatron, are compatible with the standard model at a confidence level of less than 1% (see [1,38]), enough to claim a deviation from the Standard Model. The other precision observables are in perfect

Table 2: Precision observables: experimental results (from refs. 1,2,3) and standard model predictions.

observable	exp. (1995)	standard model prediction
M_Z (GeV)	91.1884 ± 0.0022	input
Γ_Z (GeV)	2.4963 ± 0.0032	$2.4976 \pm 0.0077 \pm 0.0033$
σ_0^{had} (nb)	41.4882 ± 0.078	$41.457 \pm 0.011 \pm 0.076$
Γ_{had}/Γ_e	20.788 ± 0.032	$20.771 \pm 0.019 \pm 0.038$
Γ_{inv} (MeV)	499.9 ± 2.5	501.6 ± 1.1
$\Gamma_b/\Gamma_{had} = R_{had}$	0.2219 ± 0.0017	0.2155 ± 0.0004
Γ_c/Γ_{had}	0.1540 ± 0.0074	0.1713 ± 0.0002
A_b	0.841 ± 0.053	0.9346 ± 0.0006
ρ_ℓ	1.0044 ± 0.0016	1.0050 ± 0.0023
s_ℓ^2 (LEP)	0.23186 ± 0.00034	0.2317 ± 0.0012
$s_e^2(A_{LR})$ LEP+SLC	0.23049 ± 0.00050 0.23143 ± 0.00028	0.2317 ± 0.0012
M_W (GeV)	80.26 ± 0.16	80.36 ± 0.18

agreement with the Standard Model. Note that the experimental value for ρ_ℓ exhibits the presence of genuine electroweak corrections by nearly 3 standard deviations.

The W mass prediction is obtained by Eqs. (10-12) from M_Z, G_μ, α and M_H, m_t. The quantity s_W^2 resp. the ratio M_W/M_Z is indirectly measured in deep-inelastic neutrino scattering, in particular in the NC/CC neutrino cross section ratio for isoscalar targets. The present world average from CCFR, CDHS and CHARM, including the new CCFR result [44]

$$s_W^2 = 1 - M_W^2/M_Z^2 = 0.2253 \pm 0.0047$$

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

Standard model fits: Assuming the validity of the standard model a global fit to all electroweak results from LEP, SLD, $p\bar{p}$ and νN constrains the parameters m_t, α_s as follows: [1,2,45]

$$m_t = 178 \pm 8^{+17}_{-20}\,\text{GeV}, \quad \alpha_s = 0.123 \pm 0.004 \pm 0.002 \quad (25)$$

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.

The indirect determination of the W mass from LEP/SLD data,

$$M_W = 80.359 \pm 0.055^{+0.013}_{-0.024}\,\text{GeV}\,,$$

is in best agreement with the direct measurement (see table 2). Moreover, the value obtained for α_s at M_Z coincides with the one measured from others than electroweak observables at the Z peak [39].

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 $M_H < 600$ GeV with approximately 95% C.L. [1,2]. Similar results with bounds on M_H which are 100-200 MeV higher, based on the electroweak data from the winter conferences, have been obtained in [42,43].

Low energy results: The cross section for μ-neutrino electron scattering and the electroweak mixing angle measured by the CHARM II Collaboration [46] agree with the standard model values:

$$\begin{aligned} \sigma(\nu e)/E_\nu &= 16.51 \pm 0.93) \cdot 10^{-42} cm^2 GeV^{-1} \\ (\text{SM} &: 17.23 \cdot 10^{-42}) \\ \sin^2\theta_{\nu e} &= 0.2324 \pm 0.0083\,. \end{aligned} \quad (26)$$

The mixing angle coincides with the result on s_ℓ^2 from the Z, table 2, as expected by the theory. The major loop contributions in the difference, the different scales and the neutrino charge radius, largely cancel each other by numerical coincidence [41].

The recent results from the CLEO Collaboration [47] on the flavor changing B decays, the branching ratio $BR(B \to X_s\gamma) = (2.32 \pm 0.67) \cdot 10^{-4}$ and the inclusive photon spectrum, are fully consistent with the standard model predictions based on the loop induced $b \to s\gamma$ transition [48].

4 Future tests of the Standard Model

4.1 Higgs bosons

The minimal model with a single scalar doublet is the simplest way to implement the electroweak symmetry breaking. The experimental result that the ρ-parameter is very close to unity is a natural feature of models with doublets and singlets. In the standard model, the mass M_H of the Higgs boson appears as the only additional parameter beyond the vector boson and fermion masses. M_H cannot be predicted but has to taken from experiment. The present lower limit (95% C.L.) from the search at LEP [49] is 65 GeV. Indirect determinations of M_H from precision data have already been discussed in section 3. The indirect mass bounds depend sensitively on small changes in the input data, and their reliability suffers at present from averaging data points which fluctuate by several standard deviations. As a general feature, it appears that the data prefer light Higgs bosons.

There are also a theoretical constraints on the Higgs mass from vacuum stability and absence of a Landau pole [50], and from lattice calculations [51]. A recent calculation of the decay width for $H \to W^+W^-$ in the large M_H limit in 2-loop order [52] has shown that the 2-loop contribution exceeds the 1-loop term in size (same sign) for $M_H > 930$ GeV. The requirement of applicability of perturbation theory therefore puts a stringent upper limit on the Higgs mass.

Higgs boson searches at LEP2 and future high energy hadron and e^+e^- colliders require precise predictions for the Higgs production and decay signatures together with detailed background studies. Improved calculations for the most relevant Higgs decays including higher order contributions have become available for

- $H \to b\bar{b}$ for $M_H < 2m_t$ in order $O(\alpha_s^2)$ [53,54], and $O(\alpha_s G_\mu m_t^2)$ [55] as well as $O(\alpha_s^2 G_\mu m_t^2)$ [56];
- $H \to gg(g)$ up to order $O(\alpha_s^3)$ [53];
- $H \to ZZ, WW$ for large M_H in electroweak 2-loop order [52].

The QCD corrections for Higgs production at the LHC has been completed [57], with the result of a significant enhancement by the next order QCD contributions.

Higgs signal versus background studies were performed for the process $e^+e^- \to b\bar{b}\ell\bar{\ell}$ at tree level order, both (semi-)analytically [58] and by Monte Carlo methods [59]. Current work is going on in the topical LEP200 Workshop. An overview with more details on the present theoretical status of Higgs physics can be found in these proceedings [60].

4.2 W bosons

W mass measurements at LEP2 with an error of about 40 MeV and tests of the trilinear vector boson self couplings [61] require standard model calculations for the process $e^+e^- \to W^+W^- \to 4f$ and the corresponding 4-fermion background processes at the accuracy level of 1%. A status report can be found in ref. [62]. One of the specific problems in the theoretical description of the production process for off-shell W bosons is the presence of the width term in the W propagator which violates gauge invariance, yielding gauge dependent amplitudes. As a solution it has been proposed [63] to take into account also the imaginary part in the $WW\gamma$ vertex from the light fermion triangle loops. This prescription is in a accordance with gauge invariance and cures the Ward identities between 2- and 3-point functions involving $W^\pm$ and γ.

4.3 g-2 for muons

The anomalous magnetic moment of the muon,

$$a_\mu = \frac{g_\mu - 2}{2} \tag{27}$$

provides a precision test of the standard model at low energies. Within the present experimental accuracy of $\Delta a_\mu = 840 \cdot 10^{-11}$, theory and experiment are in best agreement, but the electroweak loop corrections are still hidden in the noise. A new experiment, E 821 at Brookhaven National Laboratory [64], is being prepared for 1996 to reduce the experimental error down to 40 ± 10^{-11} and hence will become sensitive to the electroweak loop contribution, which at the 1-loop level [65] amounts to $195 \cdot 10^{-11}$.

For this reason the standard model prediction has to be known with comparable precision. Recent theoretical work has contributed to reduce the theoretical uncertainty by calculating the electroweak 2-loop terms [66,67,68] and updating the contribution from the hadronic photonic vacuum polarization [9]

$$a_\mu^{had}(\text{vacuum pol.}) = (7024 \pm 153) \cdot 10^{-11}$$

which agrees within the error with the result of [69]. The main sources for the theoretical error at present are the hadronic vacuum polarization and the light-by-light scattering mediated by quarks, as part of the 3-loop hadronic contribution [70,71]. Table 3 shows the breakdown of a_μ. The hadronic part is supplemented by the higher order α^3 vacuum polarization effects [72] but is without the light-by-light contribution, where the situation is unclear at present.

The 2-loop electroweak contribution turns out to be as big in size as the expected experimental error. The dominating theoretical uncertainty at present is the error in the hadronic vacuum polarization which can only be improved by new measurements of the cross section for $e^+e^- \to$ *hadrons* in the low energy range. But also the the contribution involving light-by-light scattering needs clarification in order to reduce the theoretical error.

Table 3: Contributions Δa_μ to the muonic anomalous magnetic moment and their theoretical uncertainties, in units of 10^{-11}.

source	Δa_μ	error
QED [73]	116584708	5
hadronic [9,72]	6934	153
EW, 1-loop [65]	195	
EW, 2-loop [67] (anomaly graphs)	-17	3
EW, 2-loop [66] (all fermionic graphs)	-23	3
EW, 2-loop [68] (bosonic graphs)	-17	2
light-by-light [70]	-36	16
light-by-light [71]	-124	50
future experiment		40

5 Precision data and "New Physics"

New physics in R_b? If the observed difference between the measured and calculated values of R_b is explained by a non-standard contribution $\Delta\Gamma_b$ to the partial width $\Gamma(Z \to b\bar{b})$, then also other hadronic quantities like $\Gamma_Z, R_{had}, \ldots$ are increased unless the value of α_s is reduced simultaneously. Including the new physics $\Delta\Gamma_b$ as an extra free parameter in the fit yields the values [1,2]:

$$\alpha_s = 0.102 \pm 0.008, \quad \Delta\Gamma_b = 11.7 \pm 3.8 \pm 1.4\text{MeV}.$$

The top mass is affected only marginally, shifting the central value by +3 GeV, but the impact on α_s is remarkable.

Virtual New Physics: The generalization of the aforementioned method consists in 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 [74,75]. This allows a more general analysis of the electroweak data which accommodates extensions of the minimal model affecting only the vector boson self-energies. A further quantity ϵ_b has been introduced [75] in order to parametrize specific non-universal left handed contributions to the Zbb vertex via

$$g_A^b = g_A^d(1+\epsilon_b), \quad g_V^b/g_A^b = (1-\frac{4}{3}s_d^2+\epsilon_b)(1+\epsilon_b)^{-1}. \quad (28)$$

There is a wide literature [76] in this field with various conventions.

Phenomenologically, the ϵ_i are parameters which can be determined experimentally from the electroweak precision data. An updated analysis [77] on the basis of the recent electroweak results presented at this conference [1] yields for ϵ_b the value

$$\epsilon_b = 9.9 \pm 4.5 \quad (\text{SM}: \ -6.6)$$

The large difference to the standard model value is an another way of visualizing the deviation between the measured and predicted number for the ratio R_b (table 2).

The minimal supersymmetric standard model (MSSM): The MSSM deserves a special discussion 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 $\tan\beta = v_2/v_1$, 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 [78] that light non-standard Higgs bosons as well as light stop and charginos predict larger values for the ratio R_b and thus diminish the observed difference [79,81,82,83]. Complete 1-loop calculations are meanwhile available for Δr [80] and for the Z boson observables [81,82,83].

The main results in view of the recent precision data are:
- R_c can hardly be moved towards the measured range.
- R_b can come closer to the measured value, in particular for light $\tilde{t}_R$ and light charginos.
- α_s turns out to be smaller than in the minimal model because of the reasons explained in the beginning of this section.
- There are strong constraints from the other precision observables which forbid parameter configurations shifting R_b into the observed 1σ range.

For obtaining the optimized SUSY parameter set, therefore, a global fit to all the electroweak precision data (including the top mass measurements) has to be performed, as done in refs. [82,84]. Figure 1 displays the experimental data normalized to the best fit results in the SM and MSSM, with the data from this conference [84]. For the SM, α_s identified with the experimental number, therefore the corresponding result in Figure 1 is centered at 1. The most relevant conclusions are:
(i) The difference between the experimental and theoretical value of R_b is diminished by a factor $\simeq 1/2$,
(ii) the central value for the strong coupling is $\alpha_s = 0.110$ and thus is very close to the value obtained from deep inelastic scattering,
(iii) the other observables are practically unchanged,
(iv) the χ^2 of the fit is slightly better than in the minimal model.

6 Conclusions

The experimental data for tests of the standard model have achieved an impressive accuracy. In the meantime,

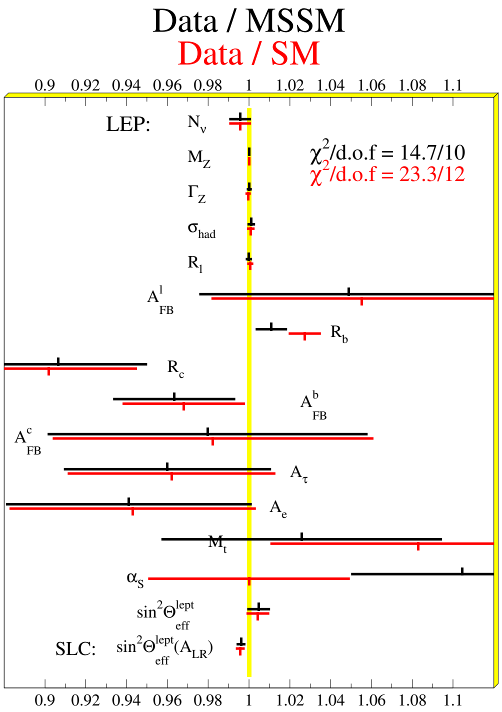

Figure 1: Experimental data normalized to the best fit results in the SM and MSSM

many theoretical contributions have become available to improve and stabilize the standard model predictions. To reach, however, a theoretical accuracy at the level 0.1% or below, new experimental data on $\Delta\alpha$ and more complete electroweak 2-loop calculations are required. The observed deviations of several σ's in R_b, R_c, A_{LR} reduce the quality of the standard model fits significantly, but the indirect determination of m_t is remarkably stable. Still impressive is the perfect agreement between theory and experiment for the whole set of the other precision observables. SUSY can improve the situtation due to an enhancement of R_b by new particles in the range of 100 GeV or even below, but it is not possible to accomodate R_c. Within the MSSM analysis, the value for α_s is close to the one from deep-inelastic scattering. In the QCD sector, a deviation from the theoretical expectation in the inclusive jet cross section at the Tevatron has been reported [85] in terms of a significant excess of jets with $E_T > 200$ GeV compared to the NLO QCD prediction. It is, however, too early to draw conclusions about new physics from that.

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