REVIEW OF ELECTROWEAK THEORY

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This talk summarizes the status of the standard model predictions for electroweak precision observables including $g-2$ for muons, and discusses the status of the standard model and the MSSM in view of the new data.

1 Introduction

Impressive experimental results have been reported at this conference on the Z boson parameters [1], the W mass [2], and the top quark mass determination [3,4] with $m_t = 175 \pm 6$ GeV.

Also a sizeable amount of theoretical work has contributed over the last few years to a steadily rising improvement of the standard model predictions (for a review see ref. [5]). The availability of both highly accurate measurements and theoretical predictions, at the level of nearly 0.1% precision, provides tests of the quantum structure of the standard model thereby probing its empirically yet untested sector, and simultaneously accesses alternative scenarios like the minimal supersymmetric extension of of the standard model (MSSM).

2 Status of precision calculations

2.1 Radiative corrections in the standard model

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 being sensitive to the loop induced quantum effects, also the Higgs sector of the standard model is 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 taken from experiment. For practical calculations the physical input quantities α, G_μ, M_Z, m_f, M_H; α_s are commonly used 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 sizeable effects in the electroweak loops deserve a special discussion:

- The light fermionic content of the subtracted photon vacuum polarization corresponds to a QED induced shift in the electromagnetic fine structure constant. The evaluation of the light quark content [6] yield the result

$$(\Delta\alpha)_{had} = 0.0280 \pm 0.0007\,. \qquad (1)$$

  Other determinations [7] 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:

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

- The electroweak mixing angle is related to the vector boson masses by

$$\sin^2\theta = 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\Delta\rho + \cdots \qquad (3)$$

  where the main contribution to the ρ-parameter is from the (t,b) doublet [8], at the present level calculated to

$$\Delta\rho = 3x_t \cdot [1 + x_t\,\rho^{(2)} + \delta\rho_{QCD}] \qquad (4)$$

  with

$$x_t = \frac{G_\mu m_t^2}{8\pi^2\sqrt{2}}\,. \qquad (5)$$

  The electroweak 2-loop part [9,10] is described by the function $\rho^{(2)}(M_H/m_t)$. $\delta\rho_{QCD}$ is the QCD correction to the leading $G_\mu m_t^2$ term [11,12]

$$\delta\rho_{QCD} = -2.86a_s - 14.6a_s^2, \quad a_s = \frac{\alpha_s(m_t)}{\pi}\,.$$

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, is in 1-loop order given by [13]:

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

The appearance of large terms in Δr requires the consideration of higher than 1-loop effects. At present, the following higher order contributions are available:

- The leading log resummation [14] of $\Delta\alpha$: $1 + \Delta\alpha \to (1 - \Delta\alpha)^{-1}$
- The incorporation of non-leading higher order terms containing mass singularities of the type $\alpha^2 \log(M_Z/m_f)$ from the light fermions [18].
- The resummation of the leading m_t^2 contribution [15] in terms of $\Delta\rho$ in Eq. (4). Moreover, the complete $O(\alpha\alpha_s)$ corrections to the self energies are available [16,17], and part of the $O(\alpha\alpha_s^2)$ terms [22].
- The $G_\mu^2 m_t^2 M_Z^2$ contribution of the electroweak 2-loop order [23].

2.3 *Z boson observables*

With M_Z as a precise input parameter, 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:

$$\begin{aligned} J_\nu^{NC} \quad & g_V^f \gamma_\nu - g_A^f \gamma_\nu\gamma_5 \qquad (6) \\ & = (\rho_f)^{1/2} \left((I_3^f - 2Q_f s_f^2)\gamma_\nu - I_3^f \gamma_\nu\gamma_5 \right) . \end{aligned}$$

with form factors ρ_f and s_f^2 for the overall normalization and the effective mixing angle.

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

$$A_f = \frac{2 g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2} . \qquad (7)$$

Measurements of the asymmetries hence are measurements of the ratios

$$g_V^f / g_A^f = 1 - 2Q_f s_f^2 \qquad (8)$$

or the effective mixing angles, respectively.

The total Z width Γ_Z can be calculated essentially as the sum over the fermionic partial decay widths. Expressed in terms of the effective coupling constants they read up to 2nd order in the fermion masses:

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

with $\left[N_C^f = 1 \text{ (leptons)}, \ = 3 \text{ (quarks)} \right]$

$$\Gamma_0 = N_C^f \frac{\sqrt{2} G_\mu M_Z^3}{12\pi},$$

and the QCD corrections $\Delta\Gamma_{QCD}^f$ for quark final states [19].

2.4 *Accuracy 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 of the hadronic contribution to $\alpha(M_Z^2)$, Eq. (2), 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 experimental precision.

The uncertainties from the QCD contributions can essentially be traced back to those in the top quark loops for the ρ-parameter. They can be combined into the following errors [20]:

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

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" [21] in ref. [5]. Table 1 shows the uncertainty in a selected set of precision observables. Quite recently (not included in table 1) the non-leading 2-loop corrections $\sim G_\mu^2 m_t^2 M_Z^2$ have been calculated [23] for Δr and s_ℓ^2. They reduce the uncertainty in M_W and s_ℓ^2 considerably, by about a factor 0.2.

Table 1: Largest half-differences among central values (Δ_c) and among maximal and minimal predictions (Δ_g) for $m_t = 175\,\mathrm{GeV}$, $60\,\mathrm{GeV} < M_H < 1\,\mathrm{TeV}$, $\alpha_s(M_Z^2) = 0.125$ (from ref.[21])

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}

3 Standard model and precision data

In table 2 the standard model predictions for Z pole observables and the W mass are put together for a light and a heavy Higgs particle with $m_t = 175$ GeV. The last column is the variation of the prediction according to $\Delta m_t = \pm 6$ GeV. The input value $\alpha_s = 0.123$ is the one from QCD observables at the Z peak[24]. Not included are the uncertainties from $\delta\alpha_s = 0.006$, which amount to 3 MeV for the hadronic Z width. The experimental results on the Z observables are from combined LEP and SLD data. ρ_l and s_l^2 are the leptonic neutral current couplings in eq. (6), obtained from partial widths and asymmetries under the assumption of lepton universality. Compared to the previous year, the deviation in R_c has disappeared and R_b is on its way towards the standard model value. On the other hand, the deviation in A_b has become somewhat stronger.

Table 2 also illustrates the sensitivity of the various quantities to the Higgs mass. The effective mixing angle turns out to be the most sensitive observable, where both the experimental error and the uncertainty from m_t are small compared to the variation with M_H. Since a light Higgs boson corresponds to a low value of s_l^2, the strongest upper bound on M_H is from A_{LR} at the SLC[25], whereas LEP data alone allow to accommodate also a relatively heavy Higgs.

Standard model fits and Higgs mass range: Assuming the validity of the standard model a global fit to all electroweak results from LEP, SLD, M_W, νN and m_t, allows to derive information on the allowed range for the Higgs mass. The impact of R_b is only marginal, whereas A_{LR} is decisive for a restrictive upper bound for M_H. From the fit one obtains[1,26]:

$$M_H = 149^{+148}_{-82}\mathrm{GeV}, \quad M_H < 450\mathrm{GeV}(95\%C.L.)\,.$$

Similar results have been obtained in[27] (updated from[28]). Without A_{LR}, the 95% C.L upper bound is shifted upwards by about 260 GeV.

These numbers do not yet include the theoretical uncertainties of the standard model predictions. The LEP-EWWG[1,29] has performed a study of the influence of the various 'options' (section 2.4) on the Higgs mass with the result that the 95% C.L. upper bound is shifted by +100 GeV to higher values. It has to be kept in mind, however, that this error estimate is based on the uncertainties as given in table 1. Since the recent improvement in the theoretical prediction[23] is going to reduce the theoretical uncertainty especially in the effective mixing angle one may expect also a significantly smaller theoretical error on the Higgs mass bounds once the 2-loop terms $\sim G_\mu^2 m_t^2 M_Z^2$ are implemented in the codes used for the fits. At the present stage the codes are without the new terms.

4 Fermion pair production above the Z resonance

Also above the Z peak, the production of fermion pairs is an important class of processes since they are the dominant ones at LEP 2. The cross sections are measurable with high accuracy: 1.2% for $e^+e^- \to \mu^+\mu^-$, and 0.7% for $e^+e^- \to hadrons$ [30]. From the theoretical side they are of special interest because box diagrams with two heavy boson exchange are no longer negligible, contributing several percent to the integrated cross section. Large QED corrections from the radiative tail of the Z resonance to both integrated cross sections and forward-backward asymmetries occur and require a careful theoretical treatment to obtain a theoretical precision of about 0.5% (see[30] for more information).

Table 2: Precision observables: experimental results[1] and standard model predictions.

observable	exp. (1996)	$M_H = 65$ GeV	$M_H = 1$ TeV	Δm_t
M_Z (GeV)	91.1863 ± 0.0020	input	input	
Γ_Z (GeV)	2.4946 ± 0.0027	2.5015	2.4923	± 0.0015
σ_0^{had} (nb)	41.508 ± 0.056	41.441	41.448	± 0.003
Γ_{had}/Γ_e	20.778 ± 0.029	20.798	20.770	± 0.002
$\Gamma_b/\Gamma_{had} = R_b$	0.2178 ± 0.0011	0.2156	0.2157	± 0.0002
$\Gamma_c/\Gamma_{had} = R_c$	0.1715 ± 0.0056	0.1724	0.1723	± 0.0001
A_b	0.867 ± 0.022	0.9350	0.9340	± 0.0001
ρ_l	1.0043 ± 0.0014	1.0056	1.0036	± 0.0006
s_l^2	0.23165 ± 0.00024	0.23115	0.23265	± 0.0002
M_W (GeV)	80.356 ± 0.125	80.414	80.216	± 0.038

5 Muon anomalous magnetic moment

The anomalous magnetic moment of the muon,

$$a_\mu = \frac{g_\mu - 2}{2} \qquad (9)$$

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 [31], is being prepared for 1997 to reduce the experimental error down to 40 ± 10^{-11} and hence will become sensitive to the electroweak loop contribution.

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 [33,34] and updating the contribution from the hadronic photonic vacuum polarization (first reference of [6])

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

which agrees within the error with the result of [35]. 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 [36,37]. Table 3 shows the breakdown of a_μ. The hadronic part is supplemented by the higher order α^3 vacuum polarization effects[38] but is without the light-by-light contribution.

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 [39]	116584706	2
hadronic [6,38]	6916	153
EW, 1-loop [32]	195	
EW, 2-loop [34]	-44	4
light-by-light [36]	-52	18
light-by-light [37]	-124	50
future experiment		40

The 2-loop electroweak contribution is as big in size as the expected experimental error. The dominating theoretical uncertainty at present is the error in the hadronic vacuum polarization. But also the contribution involving light-by-light scattering needs improvement in order to reduce the theoretical error.

6 The MSSM and precision data

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 [40] that light non-standard Higgs bosons as well as light stop and charginos predict larger values for the ratio R_b [41,43]. Complete 1-loop calculations are available for Δr [42] and for the Z boson observables [43].

For obtaining the optimized SUSY parameter set a global fit to all the electroweak precision data, including the top mass measurement, has been performed with the new data [26]. Figure 1 displays the experimental data normalized to the best fit results in the SM and MSSM, with the data from this conference. The difference between the experimental and the SM value of R_b can now be fully explained by the MSSM. Other quantities are practically unchanged. In total, the χ^2 of the fit is slightly better than in the standard model, but due to the larger numbers of parameters, the probability for the standard model is higher. A similar situations occurs for large $\tan\beta$ with light Higgs bosons h^0, A^0 around 50 GeV.

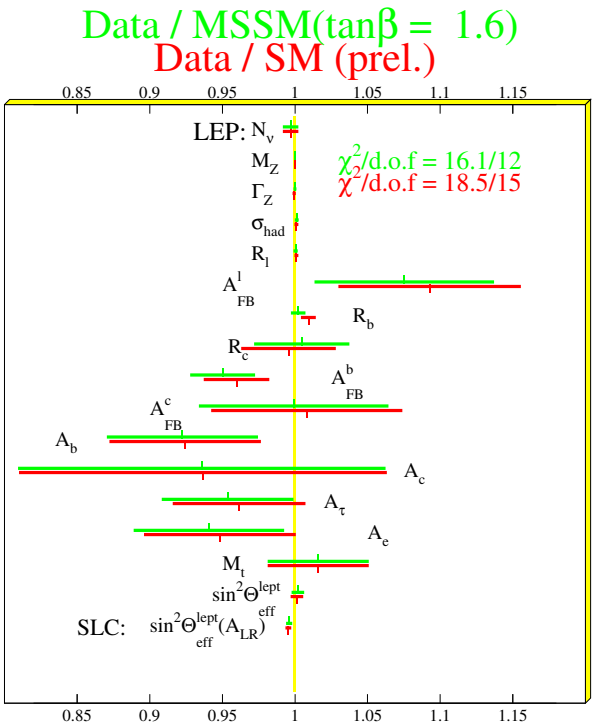

Figure 1: Experimental data normalized to the best fit results in the SM and MSSM.

In conclusion, the theoretical predictions for electroweak precision observables are reliably calculated, with the main uncertainty from $\Delta\alpha$ in (2). In view of the new data, the standard model is in a very good shape. The MSSM is competitive to the standard model, but it is no longer prefered by the data.

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