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Electroweak interactions: a theoretical overview

W. Hollik
Institut für Theoretische Physik
Universität Karlsruhe
D-76128 Karlsruhe, Germany

Plenary talk and
Theoretical Summary of the Working Group on Electroweak Interactions
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This talk summarizes topical theoretical work for tests of the electroweak standard model and of the minimal supersymmetric standard model (MSSM). The status of the standard model and the MSSM is discussed in view of recent precision data. A brief theoretical summary of the Working Group on Electroweak Interactions is included.

1. INTRODUCTION

Impressive experimental results have been obtained for the Z boson parameters [1], the W mass [1,2], and the top quark mass with $m_t = 175.6 \pm 5.5$ GeV [3]

On the other hand, 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. [4]). 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 [5] yield the result

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

  Other determinations [6] 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:

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

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

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

where the main contribution to the ρ-parameter is from the (t,b) doublet [7], at the present level calculated to

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

with

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

The electroweak 2-loop part [8,9] is described by the function $\rho^{(2)}(M_H/m_t)$. $\delta\rho_{\rm QCD}$ is the QCD correction to the leading $G_\mu m_t^2$ term [10,11]

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

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 [12]:

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2s_W^2 M_W^2}[1+\Delta r(\alpha, M_W, M_Z, M_H, m_t)]\,. \qquad (6)$$

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 [13] 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 [14].
- 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 [18].
- The non-leading $G_\mu^2 m_t^2 M_Z^2$ contribution of the electroweak 2-loop order [19]. Meanwhile also the Higgs-dependence of the non-leading m_t-terms has been calculated at two-loop order [20] (see also [21].

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:

$$\begin{aligned} J_\nu^{\rm NC} &= g_V^f\,\gamma_\nu - g_A^f\,\gamma_\nu\gamma_5 \qquad (7)\\ &= (\rho_f)^{1/2}\left((I_3^f - 2Q_f s_f^2)\gamma_\nu - I_3^f\,\gamma_\nu\gamma_5\right) \end{aligned}$$

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

$$A_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2} \qquad (8)$$

in the following way:

$$A_{\rm LR} = A_e, \quad A_{\rm FB}^f = \frac{3}{4}\,A_e A_f\,. \qquad (9)$$

Measurements of the asymmetries hence are sensitive to the ratios

$$g_V^f/g_A^f = 1 - 2Q_f s_f^2 \qquad (10)$$

or to 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:

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

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 [22]. The recently obtained non-factorizable part of the 2-loop $O(\alpha\alpha_s)$ QCD corrections [23] yields an extra negative contribution of -0.59(3) MeV for the total hadronic Z width.

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 [24]:

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

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" [25] in ref. [4]. Table 1 shows the uncertainty in a selected set of precision observables. The recently calculated non-leading 2-loop corrections $\sim G_\mu^2 m_t^2 M_Z^2$ [19] for Δr and s_ℓ^2 (not included in table 1) reduce the uncertainty in M_W and s_ℓ^2 considerably, by at least a factor 0.5.

Table 1
Largest half-differences among central values (Δ_c) and among maximal and minimal predictions (Δ_g) for $m_t = 175\,\text{GeV}$, $60\,\text{GeV} < M_H < 1\,\text{TeV}$, $\alpha_s(M_Z^2) = 0.125$ (from ref. [25])

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 this section we put together the standard model predictions for the discussed set of precision observables for comparison with the most recent experimental data [1,26]. The values for the various forward-backward asymmetries are for the pure resonance terms (9) only. The small photon and interference contributions are subtracted from the data, as well as the QED corrections. 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 for α_s is chosen as $\alpha_s = 0.118$ [27]. Not included are the uncertainties from $\delta\alpha_s = 0.003$, which amount to 1.6 MeV for the hadronic Z width, 0.038 nb for the hadronic peak cross section, and 0.019 for R_{had}. The other observables are insensitive to small variations of α_s. The experimental results on the Z observables are from LEP and SLD (A_b, A_c and s_e^2 from A_{LR}). The leptonic mixing angle determined via A_{LR} by SLD and the s_ℓ^2 average from LEP differ by about 3 standard deviations:

$$\begin{aligned} s_e^2(A_{\text{LR}}) &= 0.23055 \pm 0.00041 \\ s_\ell^2(\text{LEP}) &= 0.23196 \pm 0.00027 \, . \end{aligned}$$

The table contains the combine LEP/SLD value. ρ_ℓ and s_ℓ^2 are the leptonic neutral current couplings in eq. (7), derived from partial widths and asymmetries under the assumption of lepton universality. The table 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 $A_{\rm LR}$ at the SLC [26], whereas LEP data alone allow to accommodate also a relatively heavy Higgs (see figure 1). Further constraints on M_H are to be expected in the future from more precise M_W measurements at LEP 2 and the upgraded Tevatron.

Note that the experimental value for ρ_ℓ points out the presence of genuine electroweak corrections by 3 standard deviations. The deviation from the standard model prediction in the quantity R_b has been reduced to one standard deviation by now. Other small deviations are observed in the asymmetries: the purely leptonic $A_{\rm FB}$ is slightly higher than the standard model predictions, and $A_{\rm FB}$ for b quarks is lower. Whereas the leptonic $A_{\rm FB}$ favors a very light Higgs boson, the b quark asymmetry needs a heavy Higgs. The measured asymmetries deviate from the best fit values by 2-3 standard deviations.

The W mass prediction in table 2 is obtained from Eq. (6) (including the higher order terms) from M_Z, G_μ, α and M_H, m_t. The present experimental value for the W mass from the combined UA2, CDF and D0 results [2] is

$$M_W^{\rm exp} = 80.41 \pm 0.09\,{\rm GeV}\,, \tag{11}$$

and from LEP 2 [1]:

$$M_W^{\rm exp} = 80.48 \pm 0.14\,{\rm GeV}\,, \tag{12}$$

yielding the average given in table 2.

The quantity s_W^2 resp. the ratio M_W/M_Z can indirectly be measured in deep-inelastic neutrino-nucleon scattering. The present world average on s_W^2 from the experiments CCFR, CDHS and CHARM [28]

$$s_W^2 = 1 - M_W^2/M_Z^2 = 0.2236 \pm 0.0041 \tag{13}$$

corresponds to $M_W = 80.35 \pm 0.21$ GeV and hence is fully consistent with the direct vector boson mass measurements and with the standard theory.

The indirect determination of the W mass from the global fit to the LEP1/SLD data [1]

$$M_W = 80.323 \pm 0.042\,{\rm GeV}\,,$$

is slightly lower, but still in agreement with the direct measurement.

Standard model global fits:

In the meantime the data have reached an accuracy such that global fits with respect to both m_t and M_H as free parameters have become available [1,29–31]. The results of ref. [1] based on the most recent LEP (still preliminary) and SLD data are

$$m_t = 156^{+11}_{-9}\,{\rm GeV}, \quad M_H = 39^{+63}_{-20}\,{\rm GeV}\,.$$

Without the Tevatron constraint on the top mass, the favored range for m_t is a bit lower than the direct measurement. The reason for this behaviour is the strong impact on the upper limit of m_t from the quantity R_b.

Together with the top mass as an additional experimental data point, the global fit to all electroweak results from LEP, SLD, M_W, νN and m_t yields the following results [1] for m_t and α_s

$$m_t = 173.3 \pm 5.4\,{\rm GeV}, \quad \alpha_s = 0.120 \pm 0.003$$

and for the Higgs mass

$$M_H = 121^{+119}_{-68}\,{\rm GeV}$$

with an overall $\chi^2 = 21/15$. The input from $A_{\rm LR}$ is decisive for a restrictive upper bound for M_H. Without $A_{\rm LR}$, the 95% C.L upper bound is shifted upwards by about 260 GeV [31]. The value obtained for α_s is in very good agreement with the world average [27].

The numbers given above do not yet include the theoretical uncertainties of the standard model predictions. The LEP Electroweak Working Group [1] has performed a study of the influence of the various 'options' discussed in section 2.4 on the bounds for the Higgs mass with the result that the 95% C.L. upper bound is shifted by nearly 100 GeV to higher values, yielding

$$M_H < 430\,{\rm GeV}\,(95\%\,{\rm C.L.})\,.$$

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 [19] is going to reduce

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

observable	exp.	$M_H = 65$ GeV	$M_H = 1$ TeV	Δm_t
M_Z (GeV)	91.1863 ± 0.0019	input	input	
Γ_Z (GeV)	2.4947 ± 0.0026	2.4974	2.4881	± 0.0015
σ_0^{had} (nb)	41.489 ± 0.055	41.476	41.483	± 0.003
R_{had}	20.783 ± 0.029	20.753	20.725	± 0.002
R_b	0.2169 ± 0.0009	0.2156	0.2157	± 0.0002
R_c	0.1732 ± 0.0048	0.1724	0.1723	± 0.0001
A_{FB}^{ℓ}	0.0177 ± 0.0010	0.0170	0.0144	± 0.0003
A_{FB}^{b}	0.0979 ± 0.0022	0.1056	0.0970	± 0.0010
A_{FB}^{c}	0.0739 ± 0.0048	0.0756	0.0689	± 0.0008
A_b	0.898 ± 0.050	0.9340	0.9350	± 0.0001
A_c	0.649 ± 0.058	0.6696	0.6638	± 0.0006
ρ_ℓ	1.0039 ± 0.0013	1.0056	1.0036	± 0.0006
s_ℓ^2	0.23153 ± 0.00022	0.23114	0.23264	± 0.0002
M_W (GeV)	80.43 ± 0.08	80.417	80.219	± 0.038

the theoretical uncertainty one may expect also a significant 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 analysis is done without the new terms.

The error from the hadronic vacuum polarization is incorporated in the fit and is thus part of the result on the Higgs mass bound. The uncertainty induced from $\Delta\alpha$ is quite remarkable at the present stage (see for example the discussion in [29]).

There are also a theoretical constraints on the Higgs mass from vacuum stability and absence of a Landau pole [32], and from lattice calculations [33]. Recent calculations of the decay width for $H \to W^+W^-, ZZ$ in the large M_H limit in 2-loop order [34] have 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. The indirect Higgs mass bounds obtained from the precision analysis show, however, that the Higgs boson is well below the mass range where the Higgs sector becomes non-perturbative.

4. W BOSONS IN e^+e^- COLLISIONS

At LEP 2, pair production of on-shell W bosons can be studied experimentally allowing M_W measurements with an aimed error of about 40 MeV and tests of the trilinear vector boson self couplings. For this purpose standard model calculations for the process $e^+e^- \to W^+W^- \to 4f$ and the corresponding 4-fermion background processes are required at the accuracy level of 1%. For practical purposes, improved Born approximations are in use for both resonating and non-resonating processes, dressed by initial state QED corrections, incorporating the set of fermion loop contributions at the one-loop level in the double- and single-resonating processes (see [35] and talk by Passarino [36] in these proceedings).

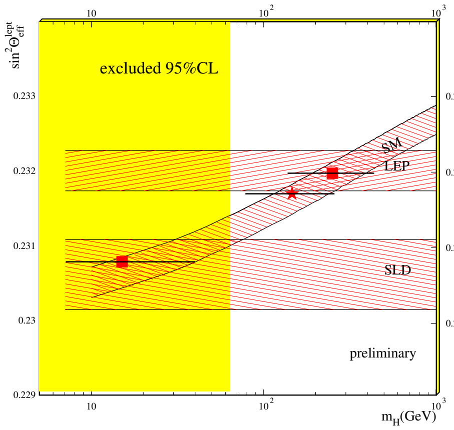

Figure 1. Dependence of the leptonic mixing angle on the Higgs mass. The theoretical predictions correspond to $m_t = 175 \pm 6$ GeV. The SLD and LEP measurements are separately shown. The star is the result of a combined fit to LEP and SLD data, the squares are for separate fits (from ref. [31])

5. ELECTROMAGNETIC DIPOLE MOMENTS

5.1. Muon anomalous magnetic moment

The anomalous magnetic moment of the muon,

$$a_\mu = \frac{g_\mu - 2}{2} \tag{14}$$

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. The new experiment E 821 at Brookhaven National Laboratory is being prepared 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 [38,39] and updating the contribution from the hadronic photonic vacuum polarization (first reference of [5])

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

which agrees within the error with the result of [40]. 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 [41, 42]. Table 3 contains the breakdown of a_μ. The hadronic part is supplemented by the higher order α^3 vacuum polarization effects [43] but is without the light-by-light contribution (see also [21]).

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 [44]	116584706	2
hadronic [5,43]	6916	153
EW, 1-loop [37]	195	
EW, 2-loop [39]	-44	4
light-by-light [41]	-52	18
light-by-light [42]	-92	32
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.

5.2. Electric dipole moments

Electric dipole moments of the fundmantal fermions are CP violating quantitites. In the standard model they are introduced via the complex phase in the CKM matrix at the three-loop level and hence are very small quantitites. A recent new standard model calculation of the electric dipole moment of the neutron [45,21] composed from the dipole moments of the constituent quarks yields the value

$$d_{\rm n} \simeq 10^{-34}\, e\,{\rm cm} \tag{15}$$

which is several orders of magnitude below the experimental limit $\mid d_{\rm n}^{\rm exp} \mid < 10^{-25}\, e\,{\rm cm}$ [46]. An experimental observation of a non-zero electric dipole moment would therefore be a clear indication for the presence of non-standard physics.

5.3. Electric dipole form factors of the top quark

In Supersymmetry, CP violating electric dipole form factors can already be induced at the one-loop level by complex values of the SUSY parameters, yielding complex coupling constants. Since the effects are enhanced for large fermion masses, the most sizeable deviations from the small standard model predictions would occur for top quarks. A study in the minimal supersymmetric standard model (MSSM) [47] has shown that the contribution to CP violating observables in top production and decay processes can reach the level of a few 10^{-3} and thus should in principle be observable at future e^+e^- colliders.

6. VIRTUAL EFFECTS FROM SUPERSYMMETRY

6.1. Precision tests of the MSSM

The MSSM is presently the most predictive framework beyond the standard 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 [48] that light non-standard Higgs bosons as well as light stop and charginos predict larger values for the ratio R_b [49,51]. Complete 1-loop calculations are available for Δr [50] and for the Z boson observables [51].

A possible mass splitting between $\tilde{b}_L$-$\tilde{t}_L$ yields a contribution to the ρ-parameter of the same sign as the standard top term. As a universal loop contribution, it enters the quantity Δr and the Z boson couplings and is thus significantly constrained by the data on M_W and the leptonic widths. Recently the 2-loop α_s corrections have been computed [52] which can amount to 30% of the 1-loop $\Delta\rho_{\tilde{b}\tilde{t}}$.

The MSSM yields a similar good description of the precision data as the standard model. A global fit [31,53] to all electroweak precision data, including the top mass measurement, shows that the χ^2 of the fit is slightly better than in the standard model, but due to the larger numbers of parameters, the probability is about the same as for the Standard Model (see [53]).

Figure 2 displays the range of predictions for M_W in the minimal model and in the MSSM. Thereby it is assumed that no direct discovery has been made at LEP2. As one can see, precise determinations of M_W and m_t can become decisive for the separation between the models. A large value of M_W, as presently experimentally observed, gives preference to the MSSM.

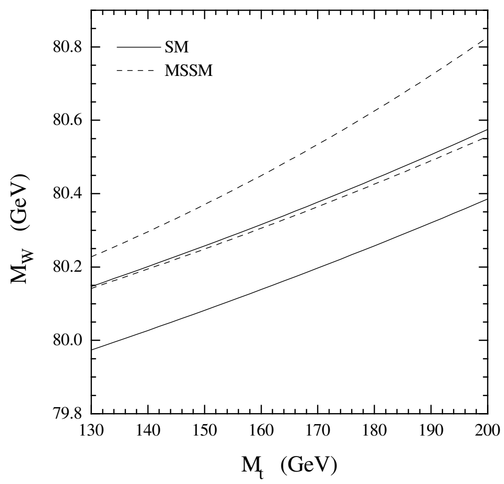

Figure 2. The W mass range in the standard model (—–) and the MSSM (- - -). Bounds are from the non-observation of Higgs bosons and SUSY particles at LEP2.

6.2. Quantum SUSY signatures in top decays

In the supersymmetric version of the standard model additional top decay modes into SUSY particles $t \to \tilde{t}\chi^0$, $\tilde{b}\chi^+$ and into charged Higgs bosons $t \to bH^+$ are possible in certain regions of the parameter space. These channels may affect the branching ratio for the standard top decay $t \to bW^+$ in a sizeable way and hence have to be treated carefully for an overall and systematic discussion of the MSSM. For the required accuracy, quantum corrections to the two-body decays have to be taken into account as well as the next-to-leading 3-particle decay channnels. Whereas the loop corrections to the standard top decay [54] are not very significant (below 10%), the supersymmetric QCD corrections to the non-standard decays are remarkable [55,56]. In particular for the decay mode $t \to bH^+$ they reach 30-50% for large values of $\tan\beta$ and compensate the large standard QCD corrections. The electroweak two-loop terms are also large, up to 50%, such that in the overall sum significant quantum corrections arise with the sign opposite to the conventional QCD corrections. This typical quantum signature may be considered as an imprint of virtual supersymmetry which remains sizeable enough even in the absence of any direct top decay into genuine SUSY particles. For a more detailed presentation see the talk by Solà in these proceedings [56].

7. CONCLUSIONS

The experimental data for tests of the standard model have achieved an impressive accuracy. In the meantime, many theoretical contributions have become available to improve and stabilize the standard model predictions. To reach, however, a theoretical accuracy at the level of 0.1% or below, new experimental data on $\Delta\alpha$ and more complete electroweak 2-loop calculations are required.

Also impressive is the overall agreement between theory and experiment for the entire set of the precision observables with a light Higgs boson in the non-perturbative regime, although a few observed deviations from the standard model predictions reduce the quality of the global fit.

The MSSM, mainly theoretically advocated, is competitive to the standard model in describing the data with about the same quality in global fits. Outside the frame of the MSSM, supersymmetry with broken R-parity provides a viable scenario to accommodate leptoquarks which can account for the observed anomaly in deep-inelastic scattering processes at HERA at high momentum transfer (see talk by Spiesberger in these proceedings [57]).

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