Precision Observables in the MSSM: Status and Perspectives

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Abstract

The current status of the theoretical predictions for the electroweak precision observables M_{W}, $\sin^2\theta_{\mathrm{eff}}$ and m_{h} within the MSSM is briefly reviewed. The impact of recent electroweak two-loop results to the quantity $\Delta\rho$ is analysed and the sensitivity of the electroweak precision observables to the top-quark Yukawa coupling is investigated. Furthermore the level of precision necessary to match the experimental accuracy at the next generation of colliders is discussed.

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1 Electroweak precision observables in the MSSM

Electroweak precision tests, i.e. the comparison of accurate measurements with predictions of the theory at the quantum level, allow to set indirect constraints on unknown parameters of the model under consideration. Within the Standard Model (SM) precision observables like the W-boson mass, M_W, and the effective leptonic weak mixing angle, $\sin^2\theta_\mathrm{eff}$, allow in particular to obtain constraints on the Higgs-boson mass of the SM. In the Minimal Supersymmetric extension of the SM (MSSM), on the other hand, the mass of the lightest $\mathcal{CP}$-even Higgs boson, m_h, can be predicted in terms of the mass of the $\mathcal{CP}$-odd Higgs boson, M_A, and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. Via radiative corrections it furthermore sensitively depends on the scalar top and bottom sector of the MSSM. Thus, within the MSSM a precise measurement of M_W, $\sin^2\theta_\mathrm{eff}$ and m_h allows to obtain indirect information in particular on the parameters of the Higgs and scalar top and bottom sector.

The status of the theoretical predictions for m_h within the MSSM has recently been reviewed in Ref. [1]. The theoretical predictions, based on the complete one-loop and the dominant two-loop results, currently have an uncertainty from unknown higher-order corrections of about ± 3 GeV, while the parametric uncertainty from the experimental error of the top-quark mass presently amounts to about ± 5 GeV.

For the electroweak precision observables within the SM very accurate results are available. This holds in particular for the prediction for M_W, where meanwhile all ingredients of the complete two-loop result are known. The remaining theoretical uncertainties from unknown higher-order corrections within the SM are estimated to be [2–4]

$$\mathrm{SM}: \quad \delta M_\mathrm{W}^\mathrm{th} \approx \pm 6 \text{ MeV}, \quad \delta\sin^2\theta_\mathrm{eff}^\mathrm{th} \approx \pm 7\times 10^{-5}. \tag{1}$$

They are smaller at present than the parametric uncertainties from the experimental errors of the input parameters m_t and $\Delta\alpha_\mathrm{had}$. The experimental errors of $\delta m_\mathrm{t} = \pm 5.1$ GeV [5] and $\delta(\Delta\alpha_\mathrm{had}) = 36\times 10^{-5}$ [5] induce parametric theoretical uncertainties of

$$\begin{aligned} \delta m_\mathrm{t}: &\quad \delta M_\mathrm{W}^\mathrm{para} \approx \pm 31 \text{ MeV}, \qquad \delta\sin^2\theta_\mathrm{eff}^\mathrm{para} \approx \pm 16\times 10^{-5}, \\ \delta(\Delta\alpha_\mathrm{had}): &\quad \delta M_\mathrm{W}^\mathrm{para} \approx \pm 6.5 \text{ MeV}, \qquad \delta\sin^2\theta_\mathrm{eff}^\mathrm{para} \approx \pm 13\times 10^{-5}. \end{aligned} \tag{2}$$

For comparison, the present experimental errors of M_W and $\sin^2\theta_\mathrm{eff}$ are [5]

$$\delta M_\mathrm{W}^\mathrm{exp} \approx \pm 34 \text{ MeV}, \quad \delta\sin^2\theta_\mathrm{eff}^\mathrm{exp} \approx \pm 17\times 10^{-5}. \tag{3}$$

At one-loop order, complete results for the electroweak precision observables M_W and $\sin^2\theta_\mathrm{eff}$ are also known within the MSSM [6, 7]. At the two-loop level, the leading corrections in $\mathcal{O}(\alpha\alpha_\mathrm{s})$ have been obtained [8], which enter via the quantity $\Delta\rho$,

$$\Delta\rho = \frac{\Sigma_\mathrm{Z}(0)}{M_\mathrm{Z}^2} - \frac{\Sigma_\mathrm{W}(0)}{M_\mathrm{W}^2}. \tag{4}$$

It parameterises the leading universal corrections to the electroweak precision observables induced by the mass splitting between fields in an isospin doublet [9]. $\Sigma_\mathrm{Z,W}(0)$ denote the transverse parts of the unrenormalised Z- and W-boson self-energies at zero momentum transfer, respectively. The induced shifts in $M_{\rm W}$ and $\sin^2\theta_{\rm eff}$ are in leading order given by (with $1-s_{\rm W}^2 \equiv c_{\rm W}^2 = M_{\rm W}^2/M_{\rm Z}^2$)

$$\delta M_{\rm W} \approx \frac{M_{\rm W}}{2}\frac{c_{\rm W}^2}{c_{\rm W}^2-s_{\rm W}^2}\Delta\rho, \quad \delta\sin^2\theta_{\rm eff} \approx -\frac{c_{\rm W}^2 s_{\rm W}^2}{c_{\rm W}^2-s_{\rm W}^2}\Delta\rho. \tag{5}$$

For the gluonic corrections, results in $\mathcal{O}(\alpha\alpha_{\rm s})$ have also been obtained for the prediction of $M_{\rm W}$ [10]. The comparison with the contributions entering via $\Delta\rho$ showed that in this case indeed the full result is well approximated by the $\Delta\rho$ contribution. Contrary to the SM case, the two-loop $\mathcal{O}(\alpha\alpha_{\rm s})$ corrections turned out to increase the one-loop contributions, leading to an enhancement of up to 35% [8].

Recently the leading two-loop corrections to $\Delta\rho$ at $\mathcal{O}(\alpha_{\rm t}^2)$, $\mathcal{O}(\alpha_{\rm t}\alpha_{\rm b})$, $\mathcal{O}(\alpha_{\rm b}^2)$ have been obtained for the case of a large SUSY scale, $M_{\rm SUSY} \gg M_{\rm Z}$ [11, 12]. These contributions involve the top and bottom Yukawa couplings and contain in particular corrections proportional to $m_{\rm t}^4$ and bottom loop corrections enhanced by $\tan\beta$. Since for a large SUSY scale the contributions from loops of SUSY particles decouple from physical observables, the leading contributions can be obtained in this case in the limit where besides the SM particles only the two Higgs doublets of the MSSM are active. In the following section these results are briefly summarised.

Comparing the presently available results for the electroweak precision observables $M_{\rm W}$ and $\sin^2\theta_{\rm eff}$ in the MSSM with those in the SM, the uncertainties from unknown higher-order corrections within the MSSM can be estimated to be at least a factor of two larger than the ones in the SM as given in eq. (1).

2 Leading electroweak two-loop contributions to $\Delta\rho$

The leading contributions of $\mathcal{O}(\alpha_{\rm t}^2)$, $\mathcal{O}(\alpha_{\rm t}\alpha_{\rm b})$ and $\mathcal{O}(\alpha_{\rm b}^2)$ to $\Delta\rho$ in the limit of a large SUSY scale arise from two-loop diagrams containing a quark loop and the scalar particles of the two Higgs doublets of the MSSM, see Ref. [12]. They can be obtained by extracting the contributions proportional to $y_{\rm t}^2$, $y_{\rm t}y_{\rm b}$ and $y_{\rm b}^2$, where

$$y_{\rm t} = \frac{\sqrt{2}\,m_{\rm t}}{v\,\sin\beta}, \quad y_{\rm b} = \frac{\sqrt{2}\,m_{\rm b}}{v\,\cos\beta}\ . \tag{6}$$

The coefficients of these terms can then be evaluated in the gauge-less limit, i.e. for $M_{\rm W}, M_{\rm Z} \to 0$ (keeping $c_{\rm W} = M_{\rm W}/M_{\rm Z}$ fixed).

In this limit the tree-level masses of the charged Higgs boson $H^\pm$ and the unphysical scalars G^0, $G^\pm$ are given by

$$m_{\rm H^\pm}^2 = M_{\rm A}^2, \quad m_{\rm G}^2 = m_{\rm G^\pm}^2 = 0. \tag{7}$$

Applying the corresponding limit also in the neutral $\mathcal{CP}$-even Higgs sector would yield for the lightest $\mathcal{CP}$-even Higgs-boson mass $m_{\rm h}^2 = 0$ and furthermore $m_{\rm H}^2 = M_{\rm A}^2$, $\sin\alpha = -\cos\beta$, $\cos\alpha = \sin\beta$, where α is the mixing angle of the neutral $\mathcal{CP}$-even states. However, in the SM the limit $M_{\rm H}^{\rm SM} \to 0$ turned out to be only a poor approximation of the result for arbitrary $M_{\rm H}^{\rm SM}$, and the same feature was found for the limit $m_{\rm h} \to 0$ within the

MSSM [11, 12]. Furthermore, the neutral $\mathcal{CP}$-even Higgs sector is known to receive very large radiative corrections. Thus, using the tree-level masses in the gauge-less limit turns out to be a very crude approximation. It therefore is useful to keep the parameters of the neutral $\mathcal{CP}$-even Higgs sector arbitrary as far as possible (ensuring a complete cancellation of the UV-divergences), although the contributions going beyond the gauge-less limit of the tree-level masses are formally of higher order. In particular, keeping α arbitrary is necessary in order to incorporate non SM-like couplings of the lightest $\mathcal{CP}$-even Higgs boson to fermions and gauge bosons.

We first discuss the results for the $\mathcal{O}(\alpha_t^2)$ corrections, which are by far the dominant subset within the SM, i.e. the $\mathcal{O}(\alpha_t\alpha_b)$ and $\mathcal{O}(\alpha_b^2)$ corrections can safely be neglected within the SM. The same is true within the MSSM for not too large values of $\tan\beta$. In this case no further relations in the neutral $\mathcal{CP}$-even Higgs sector are necessary, i.e. the parameters m_h, m_H and α can be kept arbitrary in the evaluation of the $\mathcal{O}(\alpha_t^2)$ corrections. For these contributions also the top Yukawa coupling y_t can be treated as a free parameter, i.e. it is not necessary to use eq. (6). This allows to study the sensitivity of the electroweak precision observables to variations in the top Yukawa coupling.

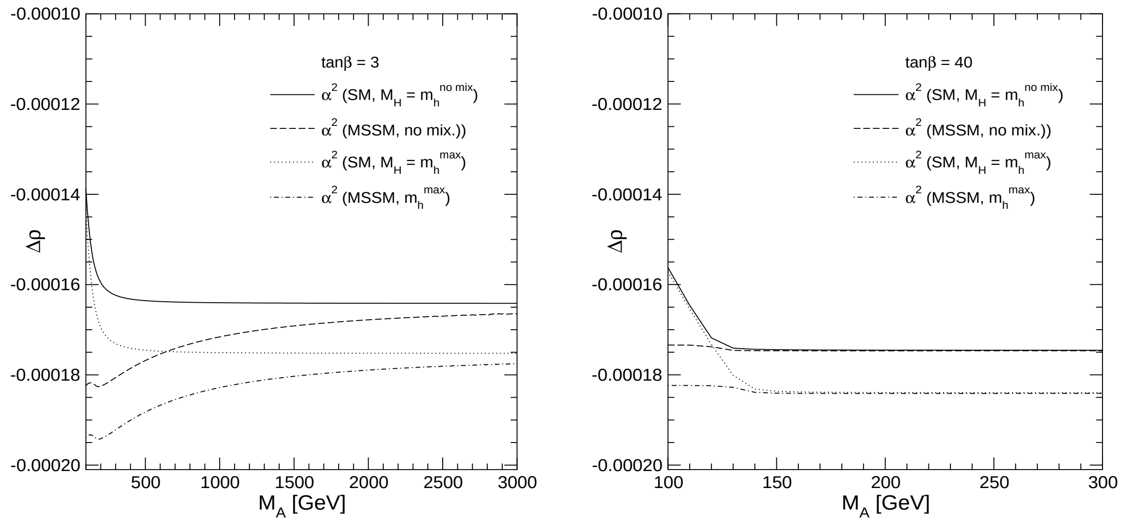


Figure 1: The $\mathcal{O}(\alpha_t^2)$ MSSM contribution to $\Delta\rho$ in the m_h^{max} and the no-mixing scenario is compared with the corresponding SM result with $M_H^{SM} = m_h$. The value of m_h is obtained in the left (right) plot from varying M_A from 100 GeV to 3000 (300) GeV, while keeping $\tan\beta$ fixed at $\tan\beta = 3$ (40).

In Fig. 1 the $\mathcal{O}(\alpha_t^2)$ contribution to $\Delta\rho$ is shown as a function of M_A for $\tan\beta = 3$ (left plot) and $\tan\beta = 40$ (right plot). The values of m_h, m_H, and α have been obtained using radiative corrections in the $t/\tilde{t}$ sector up to two-loop order as implemented in the program *FeynHiggs* [13]. The MSSM parameters have been chosen according to the m_h^{max} and no-mixing scenario benchmark scenarios [14]. For comparison, the SM result as given in Ref. [15] is also shown, where for the SM Higgs-boson mass the value of m_h has been used.

The $\mathcal{O}(\alpha_t^2)$ MSSM contribution is of $\mathcal{O}(10^{-4})$. Its absolute value is always larger than the corresponding SM result. For large values of M_A the MSSM contribution becomes SM-like. While for $\tan\beta = 3$ this decoupling proceeds rather slow and the SM value is reached only for $M_A \gtrsim 3$ TeV, for $\tan\beta = 40$ the MSSM contribution becomes SM-like already for quite small M_A values. For very small values of M_A, on the other hand, the behaviour of the SM and the MSSM contributions is very different. While the SM contribution depends sensitively on M_H^{SM}, in the MSSM for $M_A \gtrsim 100$ GeV the dependence on the Higgs boson masses is much less pronounced, see in particular the right plot of Fig. 1.

The effect of the $\mathcal{O}(\alpha_t^2)$ correction to $\Delta\rho$ on the electroweak precision observables M_W and $\sin^2\theta_{\rm eff}$ amounts to about -10 MeV for M_W and $+6\times10^{-5}$ for $\sin^2\theta_{\rm eff}$, see Ref. [12]. The 'effective' change in M_W and $\sin^2\theta_{\rm eff}$ in comparison with the corresponding SM result with the same value of the Higgs-boson mass is significantly smaller. It amounts up to -3 MeV for M_W and $+2\times10^{-5}$ for $\sin^2\theta_{\rm eff}$. The effective change goes to zero for large M_A as expected from the decoupling behaviour.

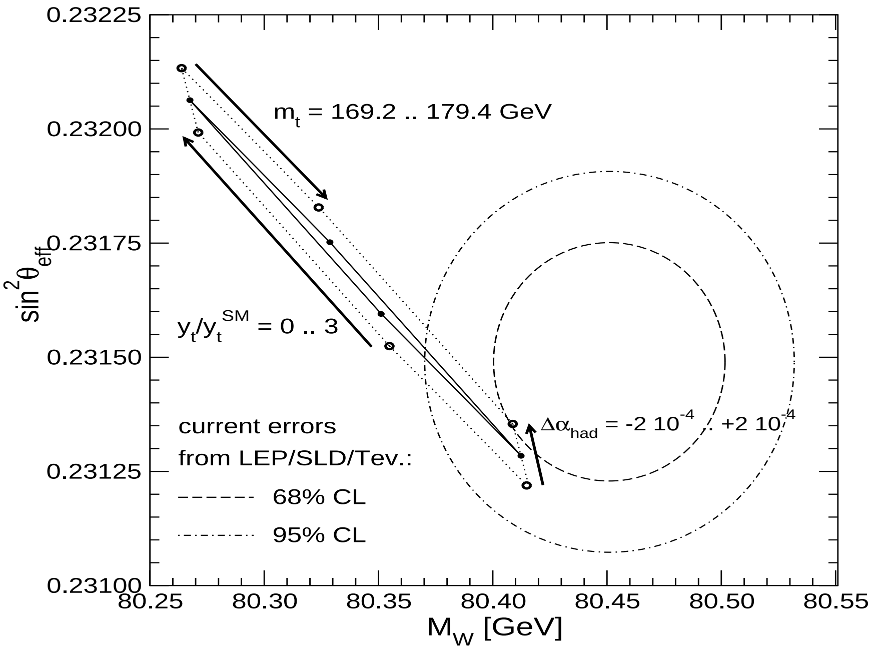
Since the top Yukawa coupling enters the predictions for the electroweak precision observables at lowest order in the perturbative expansion at $\mathcal{O}(\alpha_t^2)$, these contributions allow to study the sensitivity of the precision observables to this coupling. This sensitivity is indicated in Fig. 2, where the top Yukawa coupling in the SM and the MSSM is treated as if it were a free parameter. For simplicity, the top Yukawa coupling entering the SM contribution is scaled compared to its SM value in the following way,

$$y_t = x\, y_t^{SM}, \quad 0 \le x \le 3, \tag{8}$$

and analogously in the MSSM. The corresponding variation of the theoretical prediction for M_W and $\sin^2\theta_{\rm eff}$ is compared with the current experimental precision. The allowed 68% and 95% C.L. contours are indicated in the figure.

For the evaluation of M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM, the complete one-loop results as well as the leading two-loop $\mathcal{O}(\alpha\alpha_s)$ and $\mathcal{O}(\alpha_t^2)$ corrections have been taken into account. Since the SM prediction deviates more from the experimental central value for increasing values of M_H^{SM}, $M_H^{SM} = 114$ GeV [16] has been chosen in the figure as a conservative value. The current 1σ uncertainties in m_t and $\Delta\alpha_{\rm had}$ are also taken into account, as indicated in the plots. Varying the SM top Yukawa coupling (upper plot) yields an upper bound of $y_t < 1.3\, y_t^{SM}$ for $m_t = 174.3$ GeV and of $y_t < 2.2\, y_t^{SM}$ for $m_t = 179.4$ GeV, both at the 95% C.L. These relatively strong bounds are of course related to the fact that the theory prediction in the SM shows some deviation from the current experimental central value.

The lower plot of Fig. 2 shows the analogous analysis in the MSSM for one particular example of SUSY parameters. We have chosen a large value of $M_{\rm SUSY}$, $M_{\rm SUSY} = 1000$ GeV, in order to justify the approximation of neglecting the $\mathcal{O}(\alpha_t^2)$ contributions from SUSY loops. The other parameters are $X_t = 2000$ GeV, $M_A = 175$ GeV, $\tan\beta = 3$ and $\mu = 200$ GeV, resulting in $m_h \approx 114$ GeV (for comparison with the SM case). The SUSY contributions to M_W and $\sin^2\theta_{\rm eff}$ lead to a somewhat better agreement between the theory prediction and experiment and consequently to somewhat weaker bounds on y_t. In this example we find $y_t < 1.7\, y_t^{MSSM}$ for $m_t = 174.3$ GeV and $y_t < 2.5\, y_t^{MSSM}$ for $m_t = 179.4$ GeV, both at the 95% C.L.



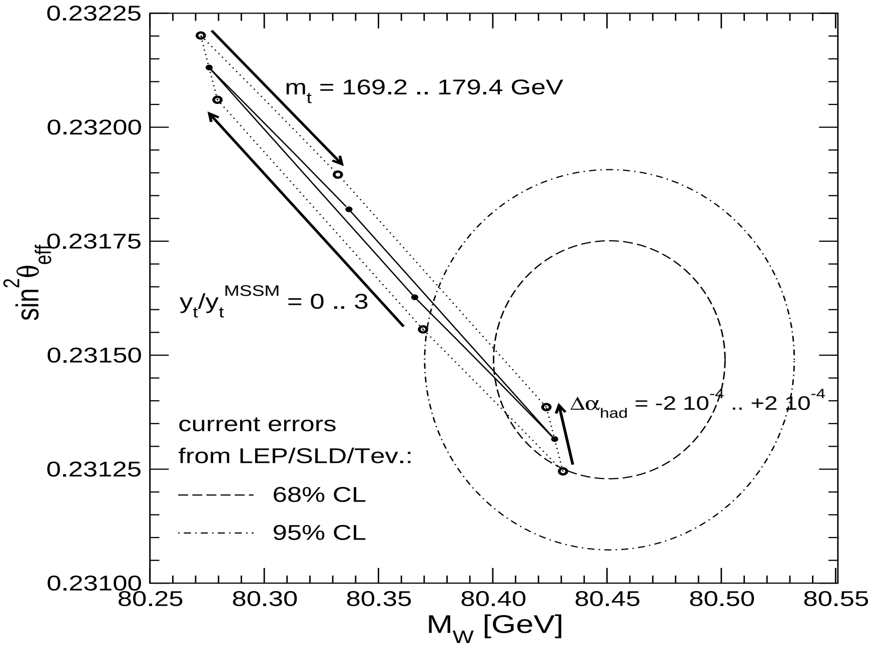


Figure 2: The effect of scaling the top Yukawa coupling in the SM (upper plot) and the MSSM (lower plot) for the observables M_{W} and $\sin^2\theta_{\mathrm{eff}}$ is shown in comparison with the current experimental precision. The variation with m_{t} and $\Delta\alpha_{\mathrm{had}}$ is shown within their current experimental errors. For the SM evaluation, $M_{\mathrm{H}}^{\mathrm{SM}}$ has been set to the conservative value of $M_{\mathrm{H}}^{\mathrm{SM}} = 114$ GeV (see text). For the MSSM evaluation the parameters are $M_{\mathrm{SUSY}} = 1000$ GeV, $X_{\mathrm{t}} = 2000$ GeV, $M_{\mathrm{A}} = 175$ GeV, $\tan\beta = 3$ and $\mu = 200$ GeV, resulting in $m_{\mathrm{h}} \approx 114$ GeV.

Including besides the $\mathcal{O}(\alpha_t^2)$ corrections also the $\mathcal{O}(\alpha_t\alpha_b)$ and $\mathcal{O}(\alpha_b^2)$ corrections to $\Delta\rho$ into the analysis requires further symmetry relations as a consequence of the SU(2) structure of the fermion doublet. Within the Higgs boson sector it is necessary, besides using eq. (7), also to use the relations for the heavy $\mathcal{CP}$-even Higgs-boson mass and the Higgs mixing angle,

$$m_H^2 = M_A^2, \quad \sin\alpha = -\cos\beta, \quad \cos\alpha = \sin\beta. \tag{9}$$

On the other hand, m_h can be kept as a free parameter. The couplings of the lightest $\mathcal{CP}$-even Higgs boson to gauge bosons and SM fermions, however, become SM-like, once the mixing angle relations, eq. (9), are used. Corrections enhanced by $\tan\beta$ thus arise only from the heavy Higgs bosons, while the contribution from the lightest $\mathcal{CP}$-even Higgs boson resembles the SM one. Furthermore, the Yukawa couplings can no longer be treated as free parameters, i.e. eq. (6) has to be employed (and the corresponding relations for the SM contribution), which ensures that the Higgs mechanism governs the Yukawa couplings.

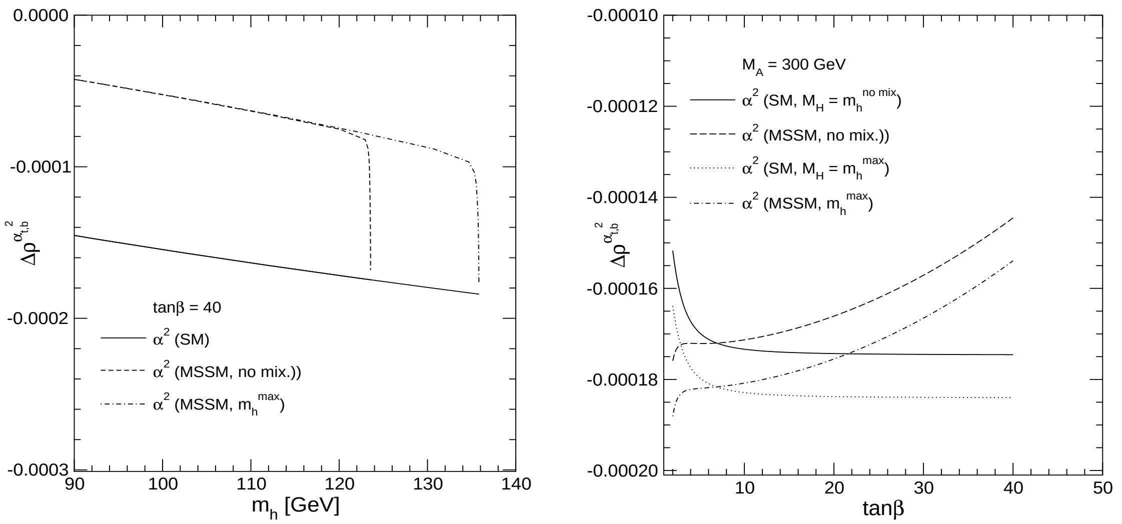


Figure 3: The $\mathcal{O}(\alpha_t^2)$, $\mathcal{O}(\alpha_t\alpha_b)$, and $\mathcal{O}(\alpha_b^2)$ MSSM contribution to $\Delta\rho$ in the m_h^{max} and the no-mixing scenario is compared with the corresponding SM result with $M_H^{SM} = m_h$. In the left plot $\tan\beta$ is fixed to $\tan\beta = 40$, while M_A is varied from 50 GeV to 1000 GeV. In the right plot M_A is set to 300 GeV, while $\tan\beta$ is varied. The bottom-quark mass is set to $m_b = 4.25$ GeV.

In Fig. 3 the result for the $\mathcal{O}(\alpha_t^2)$, $\mathcal{O}(\alpha_t\alpha_b)$, and $\mathcal{O}(\alpha_b^2)$ MSSM contributions to $\Delta\rho$ is shown in the m_h^{max} and the no-mixing scenario, compared with the corresponding SM result with $M_H^{SM} = m_h$. In the left plot $\tan\beta$ is fixed to $\tan\beta = 40$ and M_A is varied from 50 GeV to 1000 GeV. In the right plot M_A is fixed to $M_A = 300$ GeV, while $\tan\beta$ is varied. For large $\tan\beta$ the $\mathcal{O}(\alpha_t\alpha_b)$ and $\mathcal{O}(\alpha_b^2)$ contributions yield a significant effect from the heavy Higgs bosons in the loops, entering with the other sign than the $\mathcal{O}(\alpha_t^2)$ corrections, while the contribution of the lightest Higgs boson is SM-like. As one can see in Fig. 3, for large $\tan\beta$ the MSSM contribution to $\Delta\rho$ is smaller than the SM value. For large values of M_A the SM result is recovered. The effective change in the predictions for the precision observables from the $\mathcal{O}(\alpha_t\alpha_b)$ and $\mathcal{O}(\alpha_b^2)$ corrections can exceed the one from the $\mathcal{O}(\alpha_t^2)$ corrections. It can amount up to $\delta M_W \approx +5$ MeV and $\delta \sin^2\theta_{\rm eff} \approx -3 \times 10^{-5}$ for $\tan\beta = 40$.

3 Prospects for the next generation of colliders

The experimental determination of the electroweak precision observables will improve in the future at the LHC and even more at a LC with a GigaZ option, see Ref. [3] for a detailed discussion. The prospects for the measurements of $\sin^2\theta_{\rm eff}$, M_W, m_t and the Higgs-boson mass are summarised in Table 1 [3, 17].

	now	Tev. Run IIA	Run IIB	Run IIB*	LHC	LC	GigaZ
$\delta \sin^2\theta_{\rm eff} (\times 10^5)$	17	78	29	20	14–20	(6)	1.3
δM_W [MeV]	34	27	16	12	15	10	7
δm_t [GeV]	5.1	2.7	1.4	1.3	1.0	0.2	0.13
δM_H [MeV]	—	—	$\mathcal{O}(2000)$		100	50	50

Table 1: Current and anticipated future experimental uncertainties for $\sin^2\theta_{\rm eff}$, M_W, m_t and M_H, see Ref. [3] for a detailed discussion and further references.

The improvement in the measurement of m_t and prospective future improvements in the determination of $\Delta\alpha_{\rm had}$ will furthermore lead to a drastic reduction of the parametric theoretical uncertainties induced by the experimental errors of the input parameters. In Table 2 the current parametric theoretical uncertainties are compared with the prospective situation after several years of LC running, for which we have assumed $\delta m_t^{\rm future} = 0.13$ GeV. For the uncertainty in $\Delta\alpha_{\rm had}$ at this time we have assumed $\delta(\Delta\alpha_{\rm had})^{\rm future} = 5 \times 10^{-5}$. At this level of accuracy also the experimental uncertainty of the Z-boson mass, $\delta M_Z = 2.1$ MeV, will be non-negligible, which is not expected to improve in the foreseeable future. In the scenario discussed here the parametric theoretical uncertainty in M_W will be significantly smaller than the prospective experimental error, while for $\sin^2\theta_{\rm eff}$ the parametric theoretical uncertainty will be slightly larger than the prospective experimental error.

Similarly as for M_W and $\sin^2\theta_{\rm eff}$, the parametric theoretical uncertainty of the lightest $\mathcal{CP}$-even Higgs-boson mass in the MSSM induced by the experimental error of the top-quark mass will drastically improve. The prospective accuracy for m_t at the LC will reduce this uncertainty to the level of $\mathcal{O}(100)$ MeV.

In order not to be limited by the theoretical uncertainties from unknown higher-order corrections, electroweak precision tests after several years of LC running will require to reduce the latter uncertainties to the level of about ± 3 MeV for M_W and $\pm 1 \times 10^{-5}$ for $\sin^2\theta_{\rm eff}$. Achieving this level of accuracy within the MSSM or further extensions of the SM will clearly require a lot of effort. For the prediction of the lightest $\mathcal{CP}$-even Higgs-boson mass in the MSSM an improvement of the theoretical uncertainties from unknown higher-order corrections by about a factor of 30 compared to the present situation will be

	now		future	
	$\delta M_{\rm W}^{\rm para}$ [MeV]	$\delta \sin^2\theta_{\rm eff}^{\rm para} (\times 10^5)$	$\delta M_{\rm W}^{\rm para}$ [MeV]	$\delta \sin^2\theta_{\rm eff}^{\rm para} (\times 10^5)$
$\delta m_{\rm t}$	31	16	1	0.5
$\delta\alpha_{\rm had}$	6.5	13	1	1.8
$\delta M_{\rm Z}$	2.5	1.4	2.5	1.4

Table 2: Current and anticipated future parametric uncertainties for $\sin^2\theta_{\rm eff}$ and $M_{\rm W}$. For the experimental error of the top-quark mass, $\delta m_{\rm t}$, we have assumed $\delta m_{\rm t}^{\rm today} = 5.1$ GeV, $\delta m_{\rm t}^{\rm future} = 0.13$ GeV, for $\delta(\Delta\alpha_{\rm had})$ we have used $\delta(\Delta\alpha_{\rm had})^{\rm today} = 3.6 \times 10^{-4}$, $\delta(\Delta\alpha_{\rm had})^{\rm future} = 5 \times 10^{-5}$, while the experimental error of the Z-boson mass, $\delta M_{\rm Z} = 2.1$ MeV, is not expected to improve in the foreseeable future.

necessary in order to match the experimental accuracy achievable at the next generation of colliders.

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