Electroweak Precision Analyses

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Abstract

A review is given on the present status of precision tests of the Standard Model and of the Minimal Supersymmetric Standard Model (MSSM), including a discussion of the implications for the mass of virtual heavy particles via quantum effects. Expectations for high-precision analyses at future hadron and electron-positron colliders are also presented.

1 Introduction

High-precision experiments at electron-positron and hadron colliders together with the highly accurate measurements of the muon lifetime and gyromagnetic factor impose stringent tests on the standard model and possible extensions. The experimental accuracy in the electroweak observables has reached the level of the quantum effects, and requires the highest standards on the theoretical side as well. A sizeable amount of work has continuously contributed over the last two decades to a steadily rising improvement of the standard model predictions, pinning down the theoretical uncertainties to the level required for the proper interpretation of the precision data. Also for the MSSM, remarkable progress has to be reported in predicting the precision observables with similar accuracy as in the standard model. Table 1 summarizes the present experimental precision for those high-energy parameters where essential improvements are expected from future colliders experiments at the Tevatron (Run II), the LHC, and a e^+e^- Linear Collider with an additional high-luminosity GigaZ option. Moreover, the Z-boson mass and the Fermi constant with their tiny uncertainties [1], $\delta M_Z = 2.1$ GeV and $\delta G_F/G_F = 1 \cdot 10^{-5}$, will also be at our disposal. The availability of both highly accurate measurements and theoretical predictions, at the level of 0.1% precision and better, provides unique tests of the quantum structure of the models and yields indirect informations on unexplored heavy sectors.

Error for	now	Tev/LHC	LC	GigaZ
M_W [MeV]	33	15	15	6
$\sin^2\theta_{\text{eff}}$	0.00017	0.00021		0.000013
m_{top} [GeV]	5.1	2	0.2	0.13
M_{Higgs} [GeV]	–	0.1	0.05	0.05

Table 1: *Present experimental accuracies and expectations for future colliders (see [2] and references therein).*

2 Electroweak precision observables

The possibility of performing precision tests is based on the formulation of the standard model and the MSSM as renormalizable quantum field theories preserving their predictive power beyond tree-level calculations.

2.1 Muon decay and the vector-boson mass correlation

The basic physical quantity for the M_W–M_Z correlation is the muon lifetime τ_μ, which defines the Fermi constant G_F according to

$$\frac{1}{\tau_\mu} = \frac{G_F^2\, m_\mu^5}{192\pi^3}\, F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1+\frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)(1+\Delta_{\text{QED}})\,, \tag{2.1}$$

with $F(x) = 1-8x-12x^2\ln x+8x^3-x^4$. By convention, the QED corrections within the Fermi Model, Δ_{QED}, are included in this defining equation for G_F. The one-loop result for Δ_{QED} [3], has already been known for several decades; it has recently been supplemented by the two-loop correction [4], yielding

$$\Delta_{\text{QED}} = 1 - 1.81\,\frac{\alpha(m_\mu)}{\pi} + 6.7\left(\frac{\alpha(m_\mu)}{\pi}\right)^2, \quad \text{with} \quad \alpha(m_\mu) \simeq \frac{1}{135.90}\ . \tag{2.2}$$

The tree-level W-propagator effect giving rise to the (numerically insignificant) term $3m_\mu^2/(5M_W^2)$ in (2.1), is conventionally also included in the definition of G_F, although not part of the Fermi Model prediction. From the precisely measured muon-decay width the value [1] $G_F = (1.16637 \pm 0.00001)\,10^{-5}$ GeV^{-2} for the Fermi constant is derived.

Calculating the muon lifetime within the standard model or the MSSM and comparing the result with (2.1) yields the relation

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}\,(1+\Delta r)\,, \tag{2.3}$$

where the radiative corrections are summarized in the quantity Δr. Thereby, a set of infra-red divergent QED-correction graphs has to be removed, which reproduce the QED-correction factor of the Fermi-model result in (2.1). They have no influence on the relation between G_F and the model parameters.

In the standard model the quantum correction Δr was calculated for the first time by Sirlin [5] at the one-loop level. The one-loop result has been improved over the last two decades by numerically important QCD and electroweak higher-order terms, establishing thus a powerful relation that can be used to predict M_W within the SM (or possible extensions), to be confronted with the experimental result for M_W. The quantity $\Delta r = \Delta r(e, M_W, M_Z, M_H, m_t)$ depends on the entire set of input parameters. It is composed from the on-shell mass counterterms and the photon vacuum polarization from charge renormalization in the classical limit.

The photon vacuum polarization is a basic entry in the predictions for electroweak precision observables. The difference

$$\mathrm{Re}\,\hat{\Pi}^\gamma(M_Z^2) = \mathrm{Re}\,\Pi^\gamma(M_Z^2) - \Pi^\gamma(0) \tag{2.4}$$

is a finite quantity. The purely fermionic part corresponds to standard QED and does not depend on the details of the electroweak theory. It can be split into a leptonic and a hadronic contribution, yielding the quantity

$$\Delta\alpha = \Delta\alpha_{\mathrm{lept}} + \Delta\alpha_{\mathrm{had}} = -\,\mathrm{Re}\,\hat{\Pi}^\gamma_{\mathrm{lept}}(M_Z^2) - \mathrm{Re}\,\hat{\Pi}^\gamma_{\mathrm{had}}(M_Z^2)\,, \tag{2.5}$$

which represents a QED-induced shift in the electromagnetic fine structure constant

$$\alpha \;\to\; \alpha(1+\Delta\alpha)\,. \tag{2.6}$$

It can be resummed [6] according to the renormalization group, accommodating all the leading logarithms of the type $\alpha^n \log^n(M_Z/m_f)$, to give an effective fine-structure constant at the Z mass scale,

$$\alpha(M_Z^2) \;=\; \frac{\alpha}{1-\Delta\alpha}\,. \tag{2.7}$$

The leptonic content of $\Delta\alpha$ can be directly evaluated in terms of the known lepton masses, yielding at three-loop order [7]

$$\Delta\alpha_{\mathrm{lept}} \;=\; 314.97687\cdot 10^{-4}\,. \tag{2.8}$$

For the light hadronic part, perturbative QCD is not applicable and quark masses are no reasonable input parameters. Instead, the 5-flavour contribution to $\hat{\Pi}^\gamma_{\mathrm{had}}$ can be derived from experimental data with the help of a dispersion relation

$$\Delta\alpha_{\mathrm{had}} = -\,\frac{\alpha}{3\pi}\,M_Z^2\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} \mathrm{d}s'\,\frac{R^\gamma(s')}{s'(s'-M_Z^2-i\varepsilon)} \tag{2.9}$$

where

$$R^\gamma(s) = \frac{\sigma(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

is an experimental input quantity for the low energy range. A recent update including new data points from BES [8] and CMD [9] yields the value [10] $\Delta\alpha = 0.027572 \pm 0.000359$, or $\alpha^{-1}(M_Z^2) = 128.952 \pm 0.049$, respectively.

The heavy quark doublet (t, b) contributes predominantly via the ρ parameter [12]

$$\Delta\rho = \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} \tag{2.10}$$

to Δr, which thus has a simple form in the light- and heavy-fermion terms at one-loop:

$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\,\Delta\rho + \Delta r_{\rm rem}\,. \tag{2.11}$$

$\Delta\alpha$ contains the large logarithmic corrections from the light fermions and $\Delta\rho$ the quadratic correction from m_t. All other terms are collected in the remainder $\Delta r_{\rm rem}$, which has a typical size of the order ~ 0.01.

Beyond the one-loop order, higher-order 1-particle reducible and irreducible 2-loop contributions to the ρ parameter have been obtained with electroweak [11] and QCD terms [13,14]. QCD corrections Δr beyond the contribution via $\Delta\rho$ are known at $\mathcal{O}(\alpha\alpha_s)$ [15] and $\mathcal{O}(\alpha\alpha_s^2)$ [16]. First approximative electroweak two-loop calculations were performed based on expansions for asymptotically large values of M_H [17] and m_t [18].

In the meantime, the complete electroweak two-loop result in the standard model has become available: the fermionic two-loop terms [19] with all two-loop diagrams for the muon-decay amplitude containing at least one closed fermion loop, and the residual class of the two-loop purely bosonic diagrams [20,21]. Their influence is displayed in Fig. 1 for the fermionic and in Fig. 2 for the bosonic contributions, in terms of Δr and M_W.

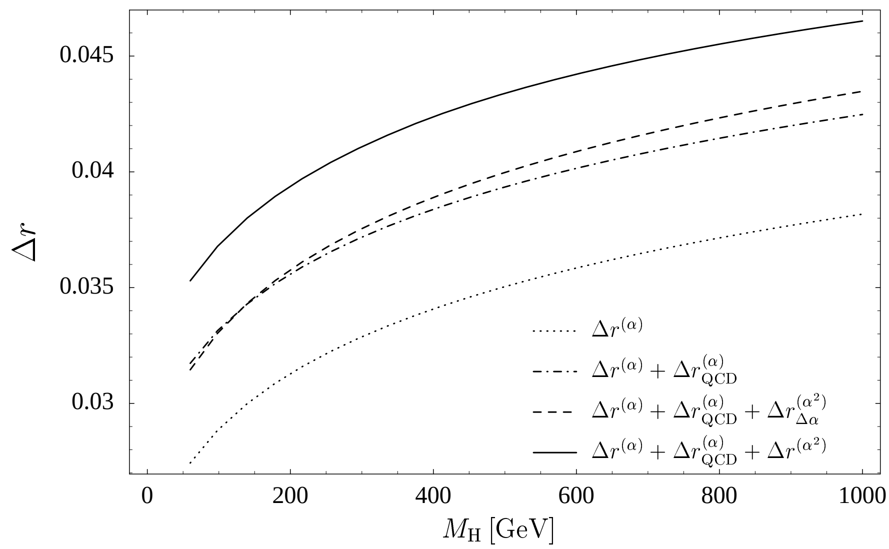

Figure 1: *Various stages of Δr, as a function of M_H. The one-loop contribution, $\Delta r^{(\alpha)}$, is supplemented by the two-loop and three-loop QCD corrections, $\Delta r^{(\alpha)}_{\rm QCD} \equiv \Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)}$, and the fermionic electroweak two-loop contributions, $\Delta r^{(\alpha^2)} \equiv \Delta r^{(N_{\rm f}\alpha^2)} + \Delta r^{(N_{\rm f}^2\alpha^2)}$. For comparison, the effect of the two-loop corrections induced by a resummation of $\Delta\alpha$, $\Delta r^{(\alpha^2)}_{\Delta\alpha}$, is shown separately.*

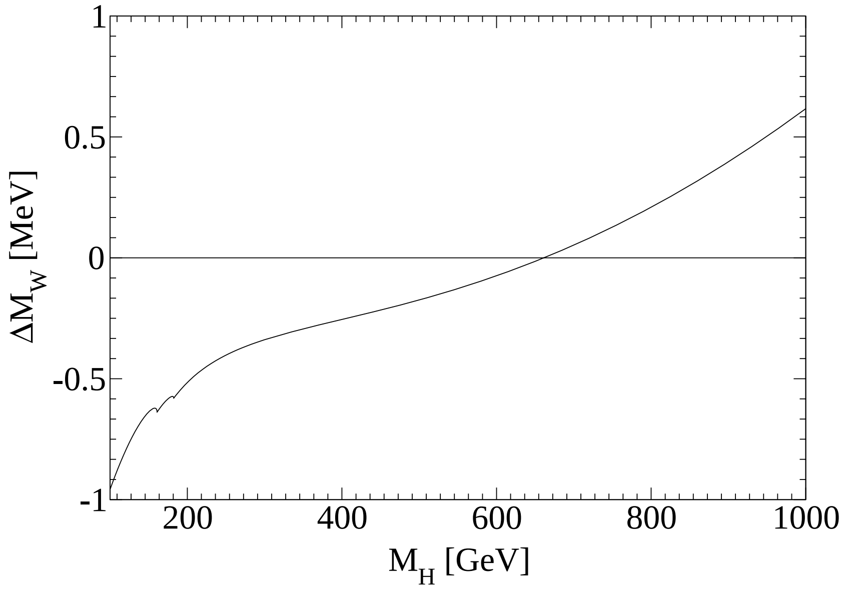

Figure 2: *The shift in M_W from the two-loop bosonic contributions to Δr (from [20]).*

2.2 *Z* boson observables

With M_Z used as a precise input parameter, together with α and G_F, the predictions for the width, partial widths and asymmetries can conveniently be calculated in terms of effective neutral current coupling constants for the various fermions (see e.g. [23]):

$$\begin{aligned} J_\nu^{\rm NC} &= \left(\sqrt{2} G_F M_Z^2\right)^{1/2} \, (g_V^f \, \gamma_\nu - g_A^f \, \gamma_\nu \gamma_5) \\ &= \left(\sqrt{2} G_F M_Z^2 \rho_f\right)^{1/2} \left((I_3^f - 2 Q_f s_f^2)\gamma_\nu - I_3^f \gamma_\nu \gamma_5\right). \end{aligned} \tag{2.12}$$

The subleading 2-loop corrections $\sim G_F^2 m_t^2 M_Z^2$ for the leptonic mixing angle [22] s_ℓ^2 have also been obtained in the meantime, as well as for ρ_ℓ [24].

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

$$A_f = \frac{2 g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}\,, \tag{2.13}$$

namely

$$A_{\rm FB} = \frac{3}{4}\, A_e A_f, \quad A_\tau^{\rm pol} = A_\tau, \quad A_{\rm LR} = A_e\,. \tag{2.14}$$

Measurements of the asymmetries hence are measurements of the ratios

$$g_V^f / g_A^f = 1 - 2 Q_f s_f^2 \tag{2.15}$$

or the effective mixing angles, respectively.

3 Standard model and precision data

3.1 Global fit and Higgs-boson mass

The Z-boson observables form LEP 1 and SLC together with M_W and the top-quark mass from LEP 2 and the Tevatron, form the set of high-energy quantities entering a global precision analysis (see [25] for a recent review). From low-energy experiments, the quantity $s_W^2 = M_W/M_Z$ can indirectly be measured in deep-inelastic neutrino–nucleon scattering. The recent NuTeV result is given by [26],

$$\begin{aligned} s_W^2 &= 0.2277 \pm 0.0013 \pm 0.0009 \\ &\quad -0.00022 \frac{m_t^2 - (175 \text{ GeV})^2}{(50 \text{ GeV})^2} \\ &\quad +0.00032 \ln(M_H/150 \text{ GeV}) \,. \end{aligned}$$

Global fits within the standard model to the electroweak precision data contain M_H as the only free parameter, yielding an upper limit to the Higgs mass at the 95% C.L. of $M_H < 193$ GeV [25], including the present theoretical uncertainties of the standard model predictions. This indirect bound and the lower bound $M_H > 114$ GeV from direct searches are compatible with a perturbative Higgs sector up to the Planck scale, as illustrated in Figure 3.

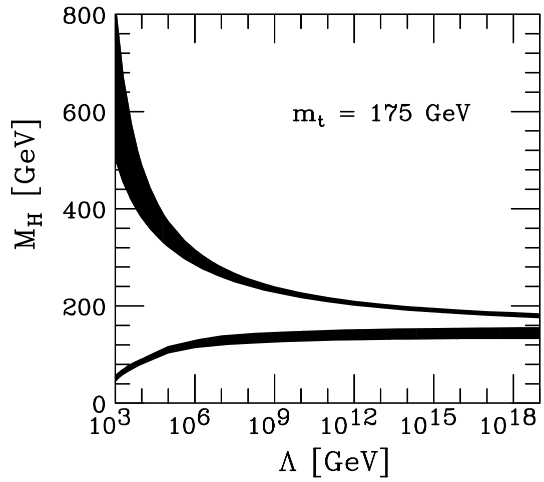

Figure 3: *Theoretical limits on the Higgs boson mass from the absence of a Landau pole and from vacuum stability (from ref [27])*

With an overall χ^2/d.o.f. = 29.7 for the best fit, the quality of the fit is not overwhelming. Figure 4, showing the deviation of the individual quantities from the standard model best-fit values, points out the forward-backward asymmetry for b quarks and the W mass from NuTeV as the dominant sources for a large χ^2. But also the direct measurement of M_W yields a somewhat larger value than the one obtained from the standard model fit.

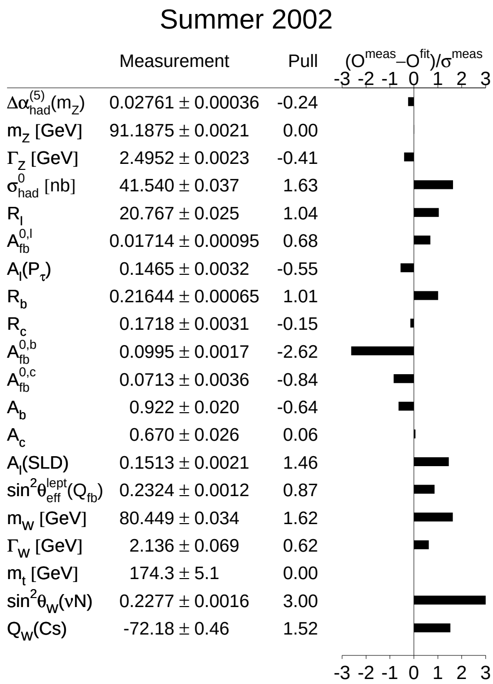

Figure 4: *Experimental results and pulls from a standard model fit [25]. Pull = obs(exp)-obs(SM)/(exp.error).*

3.2 Muon anomalous magnetic moment

The anomalous magnetic moment of the muon,

$$a_\mu = \frac{g_\mu - 2}{2} \tag{3.1}$$

provides a precision test at low energies. The new experimental result of E 821 at Brookhaven National Laboratory [28] has reached a substantial improvement in accuracy. It shows a deviation from the standard model prediction by 3 [1.6] standard deviations depending on the evaluation of the hadronic vacuum polarization from data based on e^+e^- annihilation [hadronic τ decays together with isospin rotation], as discussed in [29]. The e^+e^- data based result has been confirmed by other recent analyses [10,30].

4 The MSSM and precision data

Among the extensions of the standard model, the MSSM is the theoretically favoured scenario as the most predictive framework beyond the standard model. A definite prediction of the MSSM is the existence of a light Higgs boson with mass below ~ 135 GeV [31]. The detection of a light Higgs boson could be a significant hint for supersymmetry.

The structure of the MSSM as a renormalizable quantum field theory allows a similarly complete calculation of the electroweak precision observables as in the standard model in terms of one Higgs mass (usually taken as the CP-odd 'pseudoscalar' mass M_A) and $\tan\beta = v_2/v_1$, together with the set of SUSY soft-breaking parameters fixing the

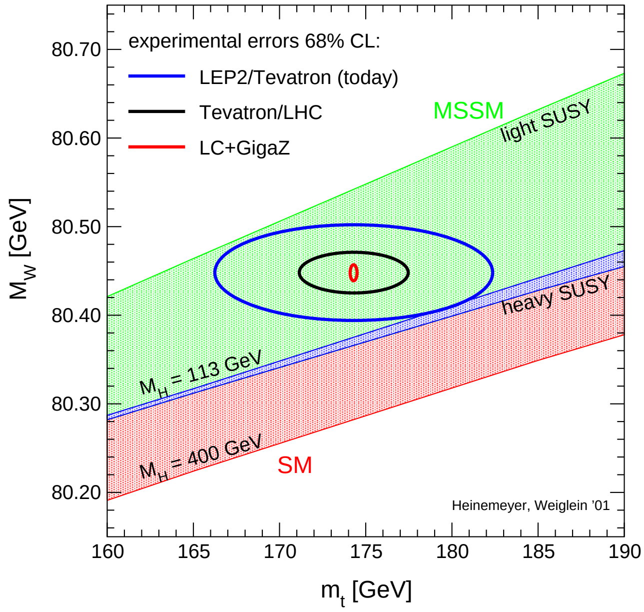

Figure 5: *The W mass range in the standard model (lower band) and in the MSSM (upper band). Bounds are from the non-observation of Higgs bosons and SUSY particles.*

chargino/neutralino and scalar fermion sectors. Complete 1-loop calculations are available for Δr [32] and for the Z boson observables [33].

A possible mass splitting between $\tilde{b}_L$ and $\tilde{t}_L$ 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 The 2-loop α_s corrections have been computed in [34], and the electroweak 2-loop contribution from the Yukawa couplings in [35]. For a more comprehensive discussion see the talk by Weiglein at this conference [36].

As an example, Figure 5 displays the range of predictions for M_W in the minimal model and in the MSSM, together with the present experimental errors and the expectations for the future colliders LHC and LC. As can be seen, the MSSM prediction is in better agreement with the present data, although not conclusive as yet. Future increase in the experimental accuracy, however, will become decisive for the separation between the models.

Especially for the muonic $g-2$ the MSSM can significantly improve the agreement between theory and experiment: relatively light scalar muons, muon-sneutrinos and charginos/neutralinos, together with a large value of $\tan\beta$ can provide a positive contribution Δa_μ which can entirely explain the difference $a_\mu^{\rm exp} - a_\mu^{\rm SM}$ [37]. Figure 6 illustrates the MSSM contribution for universal SUSY scalar mass parameters m_0 and spin-1/2 mass parameters $m_{1/2}$. For more details, see the talk by de Boer at this conference [38].

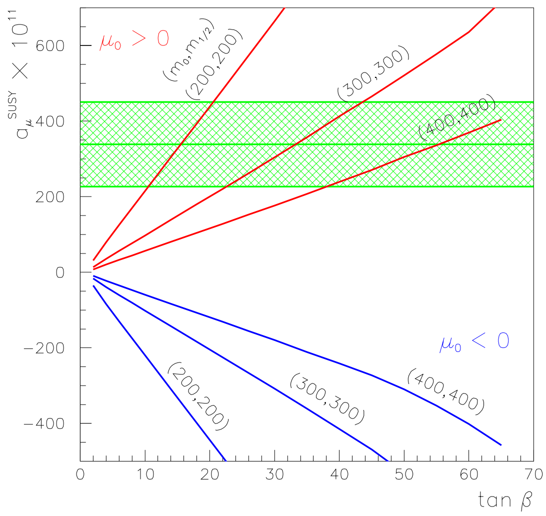

Figure 6: *Supersymmetric contribution to a_μ [38]. The deviation of the measured value from the standard model prediction is indicated by the horizontal band.*

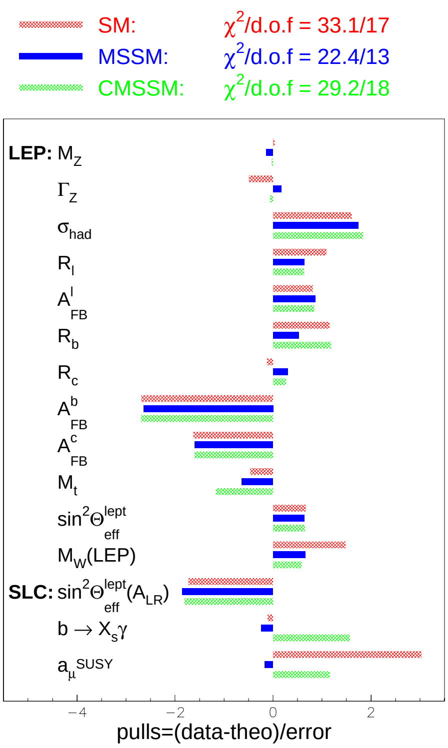

Figure 7: *Best fits in the SM and in the MSSM, normalized to the data [38]. Error bars are those from data.*

The MSSM yields a comprehensive description of the precision data, in a similar way as the standard model does. Global fits, varying the MSSM parameters, are available [39] to all electroweak precision data. They have been updated [38], showing that the description within the MSSM is slightly better than in the standard model. This is mainly due to the improved agreement for a_μ and M_W, see Figure 7.

As far as the deviation of the NuTeV result (3.1) from the standard model prediction is concerned, however, the MSSM fails to improve the situation [40].

5 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 and to reach a theoretical accuracy clearly better than 0.1%.

The MSSM, mainly theoretically advocated, is competitive to the standard model in describing the data with some improvements in specific observables, also not conclusive. Since the MSSM predicts the existence of a light Higgs boson, the detection of a Higgs particle could be an indication of supersymmetry. It is therefore highly important to study the different features of such a Higgs boson in the various models at a level of high precision as well.

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