Bounds on the Standard Higgs Boson

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Abstract. We review the status of precision electroweak physics with particular emphasis on the extraction of the Higgs boson mass. Global fit results depend strongly on the used value for the hadronic contribution to $\alpha(M_Z)$. We emphasize, however, that the general tendency for a light Higgs persists when using any of the recently obtained values for $\alpha(M_Z)$, and is also less dependent on deviating observables such as $A_{LR}$ than in the past.

Before the discovery of the top quark, precision analyses of the Standard Model (SM) were mainly focussed on constraining its mass, $m_t$, while the Higgs boson mass, $M_H$, was fixed to a set of reference values between its direct lower limit and typically 1 TeV. After the top quark was discovered [1] and its mass found to be in perfect agreement with the predictions of precision measurements at LEP and elsewhere, the interest shifted towards finding similar constraints for $M_H$.

With a first precise measurement of the left-right asymmetry, $A_{LR}$, at the SLC [2] came also for the first time a preference for a light Higgs boson from precision tests. Indeed, by changing $M_H$ from 1 TeV to 60 GeV the minimum $\chi^2$ decreased by 4.4 units. However, this observation depended entirely on the $A_{LR}$ and $R_b$ measurements, both of which deviated by more than 2 $\sigma$ from their SM predictions. Removing them resulted in a virtually flat $\chi^2(M_H)$ function [3]. $R_b$ itself is independent of $M_H$, but it favors a smaller $m_t$ and through the strong $m_t-M_H$ correlation in the $\rho$ parameter, $M_H$ is also driven to smaller values.

Subsequently the $A_{LR}$ and $R_b$ measurements moved closer to the SM, but with their smaller errors the deviations remained at the 2 $\sigma$ level, and as a result the sensitivity to $M_H$ was enhanced. The direct top mass determinations by CDF and DØ increased the sensitivity further and the minimum $\chi^2$ value now increased by more than 10 when $M_H$ was increased to 1 TeV [4]. Yet, most of the sensitivity was lost upon removing $A_{LR}$ and $R_b$, and both, central values and upper limits for $M_H$ depended strongly on only 2 input quantities, both in conflict with the prediction.

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Extraction of information on $M_H$ is also hampered by the uncertainties in the hadronic contribution to the vacuum polarization, $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$. There is a strong (70%) anticorrelation between $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$ and $M_H$.

With the increased precision of the measurements at LEP 1 [5,6] and the SLC [7], a better agreement of $R_b$ with the SM prediction ($1.3 \, \sigma$), accurate measurements of the $W$ boson mass, $M_W$, at LEP 2 [5] and the Tevatron [8,9], and interesting new developments regarding the determination of $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$ as we will discuss later, the tendency for a light Higgs became stronger. The minimum $\chi^2$ for a 1 TeV Higgs boson is now 16.6 larger than at its direct lower limit [10], and is less dependent on conflicting observations, although $A_{LR}$ continues to play an important role.

We will now discuss the current status on electroweak precision tests within the SM. Most of the results presented here are from the December 1997 off-year partial update of the Particle Data Group (PDG) [10] where more details, an extended list of references, and constraints on parameters describing physics beyond the SM can be found. For implications of electroweak precision studies for supersymmetric extensions of the Standard Model see Ref. [12]. We will conclude with a discussion of the current limits on $M_H$, its central fit values for a variety of fits, and the impact of $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$ and some very recent developments in its determination.

In Table 1 we give a list of observables used in the fits. The value of $m_t = 175 \pm 5$ GeV includes results from the dilepton, lepton plus jet, and all hadronic channels [13,14]. $\Gamma_Z$ is the total width of the $Z$ boson, $\sigma_{\text{had}}$ its hadronic peak cross section, and the $R_f$ and $A_{F,B}^{(0,f)} = \frac{3}{4} A_e A_f$ are branching ratios (normalized w.r.t. the hadronic width) and forward-backward asymmetries on the $Z$ pole, respectively [5,6]. $A_f$ is a function of the effective weak mixing angle, $s_f^2$, appearing in the $Z f f$ coupling. The two values of $s_W^2$ from deep-inelastic neutrino scattering are from CCFR [15] and the global average, respectively. Similarly, the $g_{V,A}^{\nu e}$ are from CHARM II [16] and from the $\nu e$ scattering world average. The second errors in the weak charges, $Q_W$, of atomic parity violation in Cs [17] and Tl [18] are theoretical [19,20]. The value of $\alpha_s$ [in brackets] from non-lineshape determinations [21] is for comparison only, and is not used as a fit constraint.

If we include $M_H$ as a fit parameter we find

$$M_H = 69^{+85}_{-43} \text{ GeV,}$$

with the central value slightly below the direct lower limit of 77 GeV (95% CL) [22]. The central value in Eq. (1) is 46 GeV smaller than the best fit value obtained by the LEP Electroweak Working Group (LEPEWWG) [5]. We trace the differences to a different treatment of radiative corrections and to a slightly different and more recent data set. Most importantly, inclusion of $O(\alpha^2 m_t^2)$ corrections [23] shift the extracted $M_H$ by $-17$ GeV. Also, we use the recent update for $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$ from Alemany, Davier, and Höcker [24], which drives $M_H$ smaller by another 10 GeV compared to the use of $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$ from Eidelman and Jegerlehner [25]. Our result,

$$\alpha_s = 0.1214 \pm 0.0031 \ (+0.0018),$$
TABLE 1. Principal LEP and other recent observables compared with the Standard Model predictions for $M_H = M_Z$. The first value for $M_W$ is from $p\bar{p}$ colliders [8,9], while the second includes the measurements at LEP [5]. The four values of $A_\tau$ are (i) from $A_{LR} = A_e$, the left-right asymmetry for hadronic final states [7]; (ii) the combined value from SLD including leptonic asymmetries and assuming universality; (iii) $A_\tau$ from the total $\tau$ polarization; and (iv) $A_e$ from the angular distribution of the $\tau$ polarization. The other $A_\tau$ are mixed forward-backward left-right asymmetries from SLD [5]. $\hat{s}_T^2 (A_{FB}^{0,q})$ is extracted from the hadronic charge asymmetry. The uncertainties in the SM predictions are from the fit parameters. The SM errors in $\Gamma_Z$, $R_\ell$, and $\sigma_{\text{had}}$ are completely dominated by the uncertainty in $\alpha_s$. In parentheses we show the shift in the predictions when $M_H$ is changed to 300 GeV. Older low-energy results are not listed but are included in the fits.

| Observable | Value | Standard Model |
|------------|-------|----------------|
| $m_t$ [GeV] | $175 \pm 5$ | $173 \pm 4$ (+5) |
| $M_W$ [GeV] | $80.405 \pm 0.089$ | $80.377 \pm 0.023$ ($-0.036$) |
| $M_Z$ [GeV] | $91.1867 \pm 0.0020$ | $91.1867 \pm 0.0020$ (+0.0001) |
| $\Gamma_Z$ [GeV] | $2.4948 \pm 0.0025$ | $2.4968 \pm 0.0017$ ($-0.0007$) |
| $\sigma_{\text{had}}$ [nb] | $41.486 \pm 0.053$ | $41.469 \pm 0.016$ ($-0.005$) |
| $R_\ell$ | $20.775 \pm 0.027$ | $20.754 \pm 0.020$ (+0.003) |
| $R_b$ | $0.2170 \pm 0.0009$ | $0.2158 \pm 0.0001$ ($-0.0002$) |
| $R_\tau$ | $0.1734 \pm 0.0048$ | $0.1723 \pm 0.0001$ (+0.0001) |
| $A^{(0,\ell)}_{FB}$ | $0.0171 \pm 0.0010$ | $0.0162 \pm 0.0003$ ($-0.0004$) |
| $A^{(0,b)}_{FB}$ | $0.0984 \pm 0.0024$ | $0.1030 \pm 0.0009$ ($-0.0013$) |
| $A^{(0,c)}_{FB}$ | $0.0741 \pm 0.0048$ | $0.0736 \pm 0.0007$ ($-0.0010$) |
| $A^{(0,\tau)}_{FB}$ | $0.118 \pm 0.018$ | $0.1031 \pm 0.0009$ ($-0.0013$) |
| $\hat{s}_T^2 (A_{FB}^{0,q})$ | $0.2322 \pm 0.0010$ | $0.2315 \pm 0.0002$ (+0.0002) |
| $A_t$ | $0.1550 \pm 0.0034$ | $0.1469 \pm 0.0013$ ($-0.0018$) |
| $A_b$ | $0.1411 \pm 0.0064$ | $0.1399 \pm 0.0073$ |
| $A_c$ | $0.900 \pm 0.050$ | $0.9347 \pm 0.0001$ ($-0.0002$) |
| $s_W^2 (\nu N) = 1 - M_W^2 / M_Z^2$ | $0.2236 \pm 0.0041$ | $0.2230 \pm 0.0004$ (+0.0007) |
| $g_V^{\nu\ell}$ | $-0.035 \pm 0.017$ | $-0.0395 \pm 0.0005$ (+0.0002) |
| $g_V^{\nu\tau}$ | $-0.041 \pm 0.015$ | $-0.0365 \pm 0.0004$ (+0.0002) |
| $g_A^{\nu\ell}$ | $-0.507 \pm 0.014$ | $-0.5064 \pm 0.0002$ (+0.0002) |
| $Q_W (C_s)$ | $-72.41 \pm 0.25 \pm 0.80$ | $-73.12 \pm 0.06$ (+0.01) |
| $Q_W (T)$ | $-114.8 \pm 1.2 \pm 3.4$ | $-116.7 \pm 1.0$ |
| $\Delta \alpha_{\text{had}}^{(5)} (M_Z)$ | $0.02817 \pm 0.00062$ | $0.02802 \pm 0.00049$ ($-0.000066$) |
| $\sin^2 \theta_{\text{MS}}$ | | $0.23124 \pm 0.00017$ (+0.00024) |
| $\alpha_s$ | $[0.1178 \pm 0.0023]$ | $0.1214 \pm 0.0031$ (+0.0018) |
is higher than the one in Ref. [5]. This is mainly due to $O(\alpha\alpha_s)$ vertex corrections [26] which increase the extracted $\alpha_s$ by 0.001. Taking these and other smaller differences, which are well understood, into account, the agreement with the results of the LEPEWWG is excellent. We would like to stress that this agreement is quite remarkable as the electroweak library ZFITTER [27] is based on the on-shell renormalization scheme, while we use the $\overline{\text{MS}}$ scheme throughout. It also demonstrates that once the most recent theoretical calculations, in particular Refs. [23, 26] are taken into account, the theoretical uncertainty becomes quite small and is in fact presently negligible compared to the experimental errors. The relatively large theoretical uncertainties obtained in the Electroweak Working Group Report [28] were estimated using different electroweak libraries, which did not include the full range of higher order contributions available now.

The agreement between theory and experiment is excellent. Even the largest discrepancies in $A_{LR}^{(e)}, A_{FB}^{(0,b)},$ and $A_{FB}^{(0,\tau)},$ deviate by only 2.4 $\sigma$, 1.9 $\sigma$ and 1.7 $\sigma$, respectively. There is an experimental discrepancy of 1.9 $\sigma$ between $A_\ell$ from LEP and the SLC,

$$A_\ell(\text{LEP}) = 0.1461 \pm 0.0033,$$
$$A_\ell(\text{SLD}) = 0.1547 \pm 0.0032,$$

where the LEP value is from leptonic forward-backward asymmetries and $\tau$ polarization measurements assuming lepton universality. If one considers this discrepancy as a fluctuation, one can use the average value from Eqs. (2) to extract $A_b$ from $A_{FB}^{(0,b)} = \frac{2}{3} A_e A_b$ and combine it with $A_b$ from SLD to obtain $A_b = 0.877 \pm 0.023$, which is 2.5 $\sigma$ or 6% below the SM prediction. That means a 30% radiative correction to $\hat{\kappa}_b$ defined through $\sin^2 \hat{\theta}_{\text{eff}}^b = \hat{\kappa}_b \sin^2 \hat{\theta}_{\overline{\text{MS}}}^b$ would be needed to explain the discrepancy in terms of new physics in loops. Only a new type of physics which couples at the tree level preferentially to the third generation, and which does not contradict $R_b$ (including the off-peak $R_b$ measurements by DELPHI [29]), can conceivably account for a low $A_b$ [30].

Let us now return to the implication for the Higgs mass. Results depend strongly on the used input parameter $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$. There has been a lot of activity in the recent past on this subject, and initially not all the obtained results were in agreement with each other. This is due to the difficulty of extracting phenomenologically the function $R(s)$ describing the cross section for $e^+e^-$ annihilation into hadrons from low and intermediate energy collider data. Now, the results obtained from this type of analysis are in reasonable agreement. Alternatively, one may try to employ perturbative QCD (PQCD) down to smaller energies, $\sqrt{s} \sim m_\tau$, and compute the continuum contribution to $R(s)$ theoretically. This approach was advocated by Martin and Zeppenfeld [31], and yields both smaller central values and errors for $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$. The main reason is that some of the measured cross sections lie systematically higher than the theoretical predictions in a regime where PQCD should be reliable. Very recently, Davier and H"ocker [32] improved this approach by performing a spectral moment analysis of $R(s)$ and showing that the non-perturbative
terms are under control (and very small). Hence this approach appears to be quite reliable. Moreover, a similar technique [33] applied to $\tau$ decays yields consistent results [34]. Therefore, it was concluded in Ref. [32] that PQCD can be applied down to $\sqrt{s} = m_\tau$. If we use the resulting $\Delta \alpha_{\text{had}}^{(5)}(M_Z) = 0.02784 \pm 0.00026$, (with the top quark contribution removed) for our fit, we find

$$M_H = 93^{+76}_{-46} \text{ GeV.}$$

(3)

Here the central value is above the direct lower limit. It should be stressed however, that a precise prediction for $M_H$ is impossible to obtain due to the large error, the SLD discrepancy, and the complications from $\Delta \alpha_{\text{had}}^{(5)}(M_Z)$. On the other hand, upper limits and the tendency for a light Higgs are more robust. The 90 (95)% upper limits on $M_H$ from the more experimental [24] and the more theoretical approach [32] are $M_H < 236$ (287) GeV and $M_H < 224$ (266) GeV, respectively, fortuitously in very good agreement. In order to obtain these upper limits, we have taken the Higgs exclusion curve from LEP [22] carefully into account. Since this curve extends above the quoted lower limit of 77 GeV, this results in slightly higher (more conservative) upper limits.

As a demonstration that the tendency for a light Higgs is not entirely due to the high $A_{LR}$ we remove it from the data and the result (1) changes to

$$M_H = 154^{+140}_{-82} \text{ GeV.}$$

(4)

Clearly, the central value and the errors are much larger, but this result is still compatible with the supersymmetric Higgs mass range $M_H < 150$ GeV. A less radical way to deal with deviating data is the use of PDG scale factors. Using them results in an increase of upper limits by $\mathcal{O}(100)$ GeV [10].

In conclusion, the SM of electroweak interactions is in excellent agreement with observations, with only a few deviations in some asymmetries. There is a much stronger tendency for a light Higgs boson than in the past, independently of whether one wishes to rely on PQCD or not. On the other hand, best fit values for $M_H$ are rather volatile and depend more sensitively on input parameters and details of the analysis.

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REFERENCES

1. CDF Collaboration: Abe, F., et al., Phys. Rev. Lett. 74, 2626 (1995); DØ Collaboration: Abachi, S., et al., Phys. Rev. Lett. 74, 2632 (1995).
2. SLD Collaboration: Abe, K., et al., Phys. Rev. Lett. 73, 25 (1994).
3. Erler, J., and Langacker, P., Phys. Rev. D52, 441 (1995).
4. Langacker, P., and Erler, J., e-print hep-ph/9703428.
5. ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group, and the SLD Heavy Flavour Group: Abbaneo, D., et al., Report LEPEWWG/97–02.
6. DELPHI Collaboration: Abreu, P., et al., *Z. Phys.* C67, 1 (1995), and Boudinov, E., et al., submitted to HEP 97, Jerusalem (1997).
7. SLD Collaboration: Abe, K., et al., *Phys. Rev. Lett.* 78, 2075 (1997), and Rowson, P.C., Talk presented at the 32nd Rencontres de Moriond: Electroweak Interactions and Unified Theories, Les Arcs (1997).
8. CDF Collaboration: Abe, F., et al., *Phys. Rev. Lett.* 75, 11 (1995), *Phys. Rev.* D52, 4784 (1995), and Wagner, R.G., Talk presented at the 5th International Conference on Physics Beyond the Standard Model, Balholm (1997).
9. DØ Collaboration: Abachi, S., et al., *Phys. Rev. Lett.* 77, 3309 (1996), and Abbott, B., et al., Report Fermilab–Conf–97–354–E, submitted to LP 97, Hamburg (1997).
10. Erler, J., and Langacker, P., *Electroweak Model and Constraints on New Physics*, in Ref. [11].
11. Barnett, R.M., et al., *Phys. Rev.* D54, 1 (1996) and 1997 off-year partial update for the 1998 edition available on the PDG WWW pages (URL: http://pdg.lbl.gov/).
12. Erler, J., and Pierce, D.M., e-print hep-ph/9801238.
13. CDF Collaboration: Abe, F., et al., *Phys. Rev. Lett.* 79, 1992 (1997), and Leone, S., Talk presented at QCD 97, Montpellier (1997).
14. DØ Collaboration: Abachi, S., et al., *Phys. Rev. Lett.* 79, 1197 (1997), and Abbott, B., et al., e-print hep-ex/9706014.
15. CCFR Collaboration: McFarland, K.S., et al., e-print hep-ex/9701010.
16. CHARM II Collaboration: Vilain, P., et al., *Phys. Lett.* 335B, 246 (1994).
17. Boulder: Wood, C.S., et al., *Science* 275, 1759 (1997).
18. Oxford: Edwards, N.H., et al., *Phys. Rev. Lett.* 74, 2654 (1995); Seattle: Vetter, P.A., et al., *Phys. Rev. Lett.* 74, 2658 (1995).
19. Dzuba, V.A., Flambaum, V.V., and Sushkov, O.P., e-print hep-ph/9709251.
20. Dzuba, V.A., et al., *J. Phys.* B20, 3297 (1987).
21. Hinchcliffe, I., *Quantum Chromodynamics*, in Ref. [11].
22. ALEPH, DELPHI, L3, and OPAL: Murray, W., Talk presented at HEP 97, Jerusalem (1997).
23. Degrassi, G., Gambino, P., and Vicini, A., *Phys. Lett.* B383B, 219 (1996).
24. Alemany, R., Davier, M., and Höcker, A., e-print hep-ph/9703220.
25. Eidelman, S., Davier, M., and Höcker, A., *Z. Phys.* C67, 585 (1995).
26. ZFITTER: Bardin, B., et al., Report CERN-TH.6443/92.
27. Bardin, B., et al., e-print hep-ph/9709229.
28. Bardin, B., et al., e-print hep-ph/9709229.
29. DELPHI Collaboration: Abreu, P. et al., *Z. Phys.* C70, 531 (1996) and contribution submitted to HEP 97, Jerusalem (1997).
30. Erler, J., *Phys. Rev.* D52, 28 (1995); Erler, J., Feng, J.L., and Polonsky, N., *Phys. Rev. Lett.* 78, 3063 (1997).
31. Martin, A.D., and Zeppenfeld, D., *Phys. Lett.* B345B, 558 (1995).
32. Davier, M., and Höcker, A., e-print hep-ph/9711308.
33. Le Diberder, F., and, Pich A., *Phys. Lett.* B289B, 165 (1992).
34. Höcker, A., e-print hep-ex/9703004.