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Bounds on the Standard Higgs Boson[1]

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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 χ^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 σ 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 ρ 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 σ 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 χ^2 value now increased by more than 10 when M_H was increased to 1 TeV [4]. Yet, most of the sensitvity 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, $\Delta\alpha_{\rm had}^{(5)}(M_Z)$. There is a strong (70%) anticorrelation between $\Delta\alpha_{\rm had}^{(5)}(M_Z)$ 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 σ), 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 $\Delta\alpha_{\rm had}^{(5)}(M_Z)$ as we will discuss later, the tendency for a light Higgs became stronger. The minimum χ^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 $\Delta\alpha_{\rm had}^{(5)}(M_Z)$ 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]. Γ_Z is the total width of the Z boson, $\sigma_{\rm had}$ its hadronic peak cross section, and the R_f and $A_{FB}^{(0,f)} = \frac{3}{4} A_e A_f$ 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, $\bar{s}_f^2$, appearing in the Zff 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 νe 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 α_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

$$M_H = 69^{+85}_{-43} \text{ GeV}, \tag{1}$$

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 $\mathcal{O}(\alpha^2 m_t^2)$ corrections [23] shift the extracted M_H by -17 GeV. Also, we use the recent update for $\Delta\alpha_{\rm had}^{(5)}(M_Z)$ from Alemany, Davier, and Höcker [24], which drives M_H smaller by another 10 GeV compared to the use of $\Delta\alpha_{\rm had}^{(5)}(M_Z)$ 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_ℓ 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 univerality; (iii) A_τ from the total τ polarization; and (iv) A_e from the angular distribution of the τ polarization. The other A_f are mixed forward-backward left-right asymmetries from SLD [5]. $\bar{s}_\ell^2(A_{FB}^{(0,q)})$ is extracted from the hadronic charge asymmetry. The uncertainties in the SM predictions are from the fit parameters. The SM errors in Γ_Z, R_ℓ, and $\sigma_{\rm had}$ are completely dominated by the uncertainty in α_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 ± 5	173 ± 4 $(+5)$
M_W [GeV]	80.405 ± 0.089	80.377 ± 0.023 (-0.036)
	80.427 ± 0.075	
M_Z [GeV]	91.1867 ± 0.0020	91.1867 ± 0.0020 $(+0.0001)$
Γ_Z [GeV]	2.4948 ± 0.0025	2.4968 ± 0.0017 (-0.0007)
$\sigma_{\rm had}$ [nb]	41.486 ± 0.053	41.469 ± 0.016 (-0.005)
R_ℓ	20.775 ± 0.027	20.754 ± 0.020 $(+0.003)$
R_b	0.2170 ± 0.0009	0.2158 ± 0.0001 (-0.0002)
R_c	0.1734 ± 0.0048	0.1723 ± 0.0001 $(+0.0001)$
$A_{FB}^{(0,\ell)}$	0.0171 ± 0.0010	0.0162 ± 0.0003 (-0.0004)
$A_{FB}^{(0,b)}$	0.0984 ± 0.0024	0.1030 ± 0.0009 (-0.0013)
$A_{FB}^{(0,c)}$	0.0741 ± 0.0048	0.0736 ± 0.0007 (-0.0010)
$A_{FB}^{(0,s)}$	0.118 ± 0.018	0.1031 ± 0.0009 (-0.0013)
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2322 ± 0.0010	0.2315 ± 0.0002 $(+0.0002)$
A_ℓ	0.1550 ± 0.0034	0.1469 ± 0.0013 (-0.0018)
	0.1547 ± 0.0032	
	0.1411 ± 0.0064	
	0.1399 ± 0.0073	
A_b	0.900 ± 0.050	0.9347 ± 0.0001 (-0.0002)
A_c	0.650 ± 0.058	0.6678 ± 0.0006 (-0.0008)
$s_W^2(\nu{\rm N}) = 1 - M_W^2/M_Z^2$	0.2236 ± 0.0041	0.2230 ± 0.0004 $(+0.0007)$
	0.2260 ± 0.0039	
$g_V^{\nu e}$	-0.035 ± 0.017	-0.0395 ± 0.0005 $(+0.0002)$
	-0.041 ± 0.015	
$g_A^{\nu e}$	-0.503 ± 0.017	-0.5064 ± 0.0002 $(+0.0002)$
	-0.507 ± 0.014	
$Q_W({\rm Cs})$	$-72.41 \pm 0.25 \pm 0.80$	-73.12 ± 0.06 $(+0.01)$
$Q_W({\rm Tl})$	$-114.8 \pm 1.2 \pm 3.4$	-116.7 ± 0.1
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$	0.02817 ± 0.00062	0.02802 ± 0.00049 (-0.00066)
$\sin^2\hat{\theta}_{\overline{\rm MS}}$	—	0.23124 ± 0.00017 $(+0.00024)$
α_s	$[0.1178 \pm 0.0023]$	0.1214 ± 0.0031 $(+0.0018)$

is higher than the one in Ref. [5]. This is mainly due to $\mathcal{O}(\alpha\alpha_s)$ vertex corrections [26] which increase the extracted α_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 $\overline{\rm MS}$ 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^0_{LR}, $A^{(0,b)}_{FB}$, and $A^{(0,\tau)}_{FB}$, deviate by only 2.4 σ, 1.9 σ and 1.7 σ, respectively. There is an experimental discrepancy of 1.9 σ between A_ℓ from LEP and the SLC,

$$\begin{aligned} A_\ell(\text{LEP}) &= 0.1461 \pm 0.0033, \\ A_\ell(\text{SLD}) &= 0.1547 \pm 0.0032, \end{aligned} \tag{2}$$

where the LEP value is from letponic forward-backward asymmetries and τ 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 $A^{(0,b)}_{FB} = \frac{3}{4} A_e A_b$ and combine it with A_b from SLD to obtain $A_b = 0.877 \pm 0.023$, which is 2.5 σ or 6% below the SM prediction. That means a 30% radiative correction to $\hat\kappa_b$ defined through $\sin^2\hat\theta^{\rm eff}_b = \hat\kappa_b \sin^2\hat\theta_{\overline{\rm MS}}$ 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 $\Delta\alpha^{(5)}_{\rm had}(M_Z)$. 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 $\Delta\alpha^{(5)}_{\rm had}(M_Z)$. 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 Höcker [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 τ 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 $\Delta\alpha_{\rm had}^{(5)}(M_Z) = 0.02784 \pm 0.00026$, (with the top quark contribution removed) for our fit, we find

$$M_H = 93^{+76}_{-46} \text{ GeV}. \tag{3}$$

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 $\Delta\alpha_{\rm had}^{(5)}(M_Z)$. 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

$$M_H = 154^{+140}_{-82} \text{ GeV}. \tag{4}$$

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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