PRECISION TESTS OF THE STANDARD MODEL AND THE MASS OF THE HIGGS BOSON*

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Dedicated to Wojciech Królikowski in honour of his 70th birthday

The fits to the recent precision electroweak LEP1 data and measurement of M_W are presented. We analyze the impact different measurements have on the Higgs boson mass bounds extracted from such fits.

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The LEP data and the measurement of M_W confirm the electroweak symmetry breaking by the Higgs mechanism with few per mile accuracy. For some time they are used by several theoretical groups [1–3] and by the experimental groups [4] to constrain the less precisely known parameters of the Standard Model: the top quark mass m_t, the strong coupling constant $\alpha_s(M_Z)$ and the Higgs boson mass M_h. The loop corrections to the electroweak observables are $\mathcal{O}(m_t^2)$ in the top quark mass and only $\mathcal{O}(\log M_h)$ in the Higgs boson mass. Nevertheless, the increasing precision of the data and in particular the discovery of the top quark [5, 6] improve the prospects for constraining the Higgs boson mass in a way which may be relevant for planning the future experiments for direct Higgs search.

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In this short note we present the results of such analysis using the latest available (Brussels'95) electroweak data. We analyze those fits from the point of view of their constraints on M_h. We follow the usual strategy: in terms of the best measured observables G_F, α_{EM} and M_Z we calculate M_W, all partial widths of Z^0 and all asymmetries at the Z^0 pole and determine m_t, $\alpha_s(M_Z)$ and M_h by a fit to the data. The calculation is performed in the on–shell renormalization scheme, with all "oblique" and process dependent one–loop corrections as well as the leading higher order effects included. The experimental input (*i.e.* experimental values for the electroweak observables, their errors and correlation matrices) used in the fits is summarized in Ref. [4]. The bulk of the LEP results show satisfactory agreement with the earlier reports (one should note, however, the new value $A^{b,0}_{FB} = 0.0997 \pm 0.0031$). For M_W we use 80.33 ± 0.17 GeV which is the average value of the UA2 measurement and the new measurement reported by the CDF [8] (the D0 collaboration has not published the results of their new analysis yet). When the top quark mass is included in the fit we use the value $m_t = 181 \pm 12$ GeV. For $\Delta\alpha^{\rm hadr}_{EM}$ we use the value [1] [9] 0.0280 ± 0.0007 and include it into the χ^2 fit.

The most significant changes in the LEP data are $R_b = 0.2219 \pm 0.0017$, and $R_c = 0.1540 \pm 0.0074$. Since the identification of b quarks is much better than of the c quarks experimental collaborations also quote the value $R_b = 0.2206 \pm 0.0016$ which is obtained when the value of R_c is fixed to its SM prediction $R_c = 0.172$.

The new SLD result read [13, 7]: $A^e_{LR} \equiv \mathcal{A}_e = 0.1551 \pm 0.0040$ (which corresponds to $\sin^2\theta^{\rm eff}_l = 0.23049 \pm 0.00050$). The SLD collaboration also reported for the first time [7] the results $A^b_{LR} \equiv \mathcal{A}_b = 0.841 \pm 0.053$ and $A^c_{LR} \equiv \mathcal{A}_c = 0.606 \pm 0.090$.

The new SLD data for A^e_{LR} and the LEP value still remain more than 2σ apart: although the central values are now much closer to each other, the SLD error has significantly decreased.

The newly reported results for R_b, R_c, A^b_{LR}, A^c_{LR} have drastic effects on SM fits whose quality has significantly decreased. This indicates either large fluctuations in the present data or new physics (or both). Here we adopt the first point of view and assume that the SM is the correct low energy effective theory at the electroweak scale. In this framework we critically re–examine the bounds on the Higgs boson mass in several different versions of the fit.

We begin with the results of a fit to all the LEP, SLAC and Fermilab

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[1] The result reported in the Ref. [10] has been recently updated [12, 7] and is now close to the results reported in [9]. The result of Ref. [11] is about 1σ lower than that of [9]; it is, however, based on more theoretical assumptions [7].

data described above (*i.e.* to M_W, $1 - M_W^2/M_Z^2$, Γ_Z, σ_h, $\mathcal{A}_e$, $\mathcal{A}_\tau$, $\sin^2\theta_{\rm eff}^{\rm lept}$ $\langle Q_{FB}\rangle$, R_l, $A_{FB}^{0,l}$, R_b, R_c, $A_{FB}^{0,b}$, $A_{FB}^{0,c}$, A_{LR}^e, A_{LR}^b, A_{LR}^c, m_t and $\Delta\alpha_{EM}^{\rm hadr}$). They are given in the first line of Table I and 1σ and 2σ bounds in the (m_t, M_h) plane are shown in Fig. 1. Significant upper bounds on the Higgs boson mass are obtained but the quality of the fit is poor.

TABLE I

Results of the fit to all the data [7, 8, 13]. All masses in GeV.

m_t	Δm_t	M_h	ΔM_h	$\alpha_s(M_Z)$	$\Delta\alpha_s(M_Z)$	χ^2	d.o.f.
171.0	11.1	93	$^{+189}_{-63}$	0.122	0.005	25.0	14
170.5	10.9	82	$^{+181}_{-55}$	0.122	0.005	21.1	12

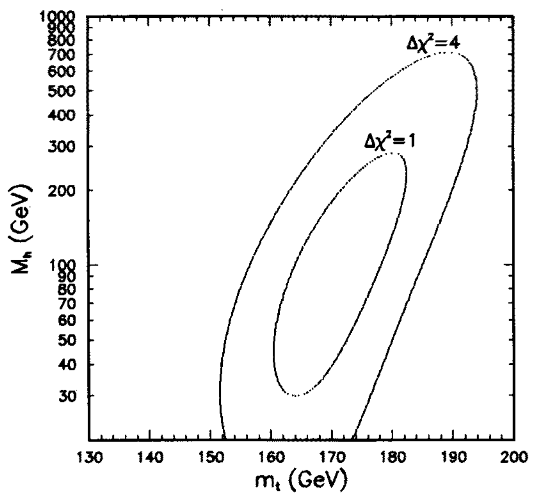

Fig. 1. Contours of $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 4$ for the χ^2 fit to all LEP, SLD and Fermilab data.

We now examine the impact of the observables which give the dominant contribution to χ^2 on the Higgs boson mass bounds. In the second line of Table I there are also given the results of a fit without the two new SLAC measurements of A_{LR}^b and A_{LR}^c. The bounds on M_h are slightly stronger and the fit is a bit better.

In the first row of Table II we show the results of a fit without R_b, R_c and without all the LR asymmetries measured by the SLD (A_{LR}^e and A_{LR}^b, A_{LR}^c). The χ^2 value is now excellent. The 1σ and 2σ contours in the (m_t, M_h) plane are shown in Fig. 2a. The bounds on M_h are very weak and critically depend on the value of m_t measured in Fermilab. Without

m_t in the fit the included data only correlate M_h with m_t (as shown also in Fig. 2a) with, however, no 2σ upper bound on M_h.

TABLE II

Results of the fit without SLD asymmetries.

m_t	R_b	m_t	Δm_t	M_h	ΔM_h	$\alpha_s(M_Z)$	$\Delta\alpha_s(M_Z)$	χ^2	d.o.f.
+	−	180.1	11.9	335	$^{+529}_{-222}$	0.125	0.005	3.2	9
−	+	152.2	$^{+14.7}_{-12.9}$	52	$^{+115}_{-29}$	0.123	0.005	9.4	9
+	+	172.4	11.2	189	$^{+326}_{-122}$	0.124	0.005	11.6	10

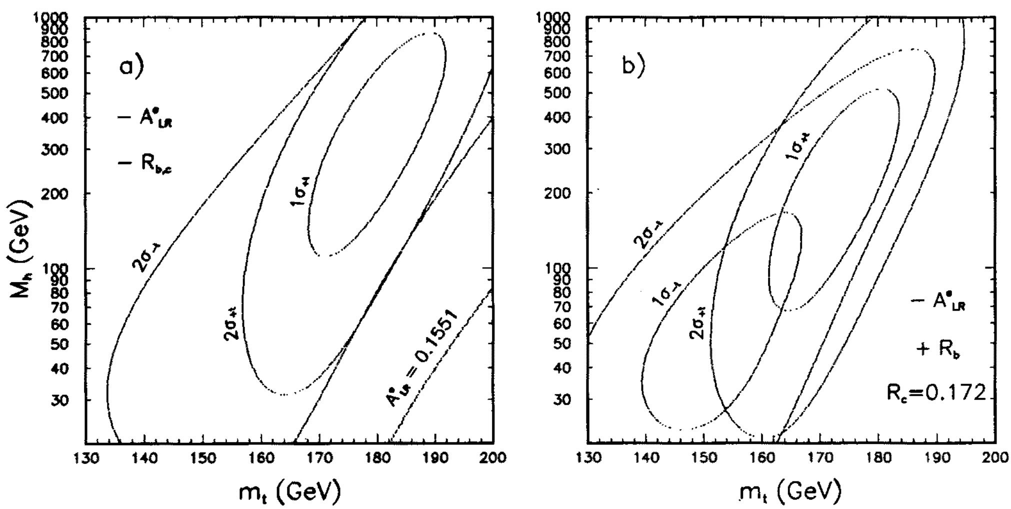

Fig. 2. Contours of $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 4$ for the χ^2 fits without the asymmetries measured at SLD (A^e_{LR}, A^b_{LR}, A^c_{LR}): a) — without R_b, R_c, b) — with $R_b = 0.2206 \pm 0.0016$ ($R_c = 0.172$ fixed) included. In both figures results of the fits without/with the Fermilab value for m_t included are marked as $1, 2\sigma_{-t}/1, 2\sigma_{+t}$ In the right bottom corner of Fig. 2a the line of constant $A^e_{LR} = 0.1551$ as measured at SLAC is also shown.

Another observable which depends on m_t but not on M_h is R_b. The measured value, to be consistent with the SM, requires very low value of m_t. Thus, inclusion of m_t and/or R_b gives the fitted value of m_t lower than the Fermilab value and, in consequence, stronger bounds on M_h. This is also shown in Table II and in Fig. 2b. Here we give the results of fits with $R_b = 0.2206 \pm 0.0016$ which is the experimental number obtained under the assumption of $R_c = 0.172$ (with the new values of R_b and R_c we get very similar bounds but the quality of the fit is poorer).

As the next step we include in the fits the SLD value of A^e_{LR}. Its effect on the fits can be understood from Fig. 2a. We show there the contour of constant $A^e_{LR} = 0.1551$. It is almost parallel to the open contours which show the $m_t - M_h$ correlation without m_t, R_b and A^e_{LR} in the fit but for the same m_t the correlated M_h is much lower. It is clear therefore that to a very good approximation the inclusion of A^e_{LR} should not alter the fitted value of m_t but strengthen the bound on M_h. This is indeed seen in Table III and in Fig. 3 (small changes in m_t compared to Table II are due to the fact that the two discussed above contours in Fig. 2 are not exactly parallel).

TABLE III

Results of the fit as in Table 2 but with A^e_{LR} included.

m_t	R_b	m_t	Δm_t	M_h	ΔM_h	$\alpha_s(M_Z)$	$\Delta\alpha_s(M_Z)$	χ^2	d.o.f.
+	−	176.7	12.0	125	$^{+271}_{-89}$	0.122	0.005	8.9	10
−	+	155.6	11.1	33	$^{+49}$	0.122	0.005	14.8	10
+	+	169.6	10.7	79	$^{+160}_{-54}$	0.122	0.005	17.1	11

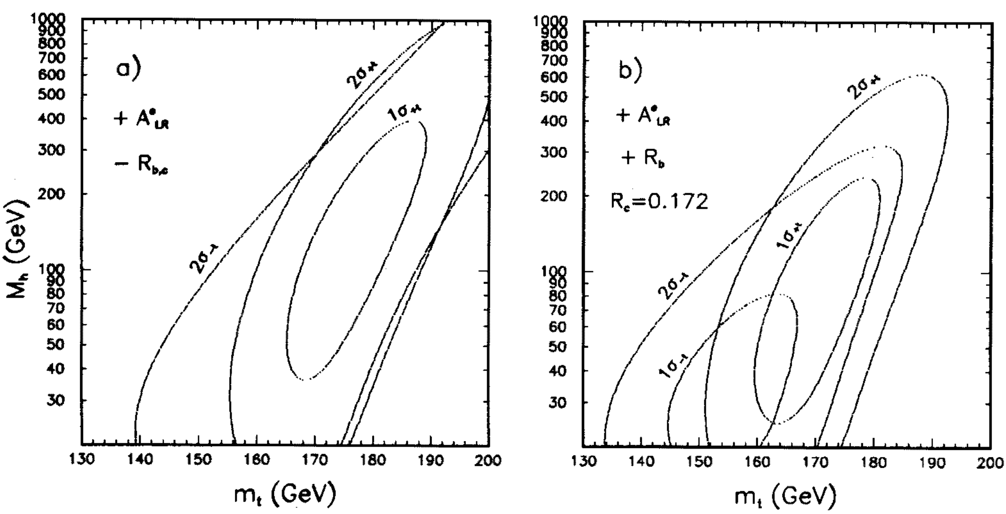

Fig. 3. As in Fig. 2 but with the SLD result for A^e_{LR} included.

The third line in Table III can be compared with the second line in Table I to see the effect of using new values of R_b and R_c instead of the value of $R_b = 0.2206 \pm 0.0016$ obtained with R_c fixed to its SM value. We conclude that the limits on M_h are stable with respect to the treatment of R_b and R_c in the fit.

To a very good approximation, the upper bounds result from a combination of $m_t - M_h$ correlation given by a fit to all but R_b electroweak data and the upper bound on m_t obtained from R_b and the direct measurement of m_t. The SLD A^e_{LR} result has important impact on $m_t - M_h$ correlation in the direction of lowering the values of M_h for given m_t (as seen in Fig. 3a).

We also note that inclusion of the SLD result in the fits gives lower value of $\alpha_s(M_Z)$. This follows from the fact that the $m_t - M_h$ values required by the value of A^e_{LR} tend to increase Γ_h, *i.e.* a lower value of $\alpha_s(M_Z)$ is now needed.

Finally one can add a few remarks related to the new values of R_b and R_c. Analysing previous electroweak data [4] and following earlier references [14, 2], we have discussed [3] the possibility of new physics in R_b and studied the upper bounds on M_h in a toy model which reproduces all the results of the SM and has an *ad hoc* correction to the $Z \to \bar{b}b$ width, so that $R_b \approx 0.22$. Then the fitted value of $\alpha_s(M_Z) = 0.108$ and the observable R_b becomes irrelevant (its contribution to $\chi^2 \approx 0$) from the point of view of the limits on M_h. In this toy model the limits on M_h were similar to the SM limits without R_b in the fit (somewhat weaker due to the smaller value of $\alpha_s(M_Z)$). With the new data the discussion remains valid provided we use the value of R_b extracted under the assumption of R_c fixed to the SM value and disregard the new R_c measurement. If, however, we include both measurements, R_b and R_c, and consider a toy model with new physics in both variables, so that $R_c \approx 0.1540$ and $R_b \approx 0.222$ then the fitted value of $\alpha_s(M_Z) = 0.178 \pm 0.005$. This is easy to understand: with $\Gamma_{Z^0 \to hadr} = 1744.8 \pm 3.0$ the sum $\Gamma_{Z^0 \to \bar{b}b} + \Gamma_{Z^0 \to \bar{c}c}$ is now much smaller than in the SM and we get $\Gamma_{Z^0 \to hadr} - \Gamma_{Z^0 \to \bar{b}b} - \Gamma_{Z^0 \to \bar{c}c}$ large. Of course, also in this toy model the observables R_b and R_c become irrelevant for the bounds on M_h and we get them similar to the SM fit without R_b in the fit. However, the large value of the fitted $\alpha_s(M_Z)$ casts doubts on the measurement of R_c, unless new physics also alters the light quark sector. (We thank H.E. Haber and C. Wagner for the discussion on this point.)

Our results, in part which overlaps, are in very good agreement with recent fits presented in [15].

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