Indirect limit on the standard model Higgs boson mass from the precision Fermilab, LEP, and SLD data

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Standard model fits are performed on the most recent leptonic and b quark Z decay data from LEP and SLD, and Fermilab data on top quark production, to obtain m_t and m_H. Poor fits are obtained, with confidence levels $\simeq 2\%$. Removing the b quark data improves markedly the quality of the fits and reduces the 95% C.L. upper limit on m_H by $\simeq 50$ GeV.

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Since the discovery of the top quark by the Collider Detector at Fermilab (CDF) and DØ Collaborations [1] and the determination of its mass with a precision of $\simeq 3\%$ [2], an important goal of the analysis of the precision electroweak data from the CERN e^+e^- collider LEP and SLAC Large Detector (SLD) [3,4] has been to establish indirect limits on the mass m_H of the standard model (SM) Higgs boson from the measurement of the effect of quantum corrections in Z decays. A 95% confidence level (C.L.) lower limit on m_H of 89.8 GeV has also recently been set in the direct search for the Higgs boson by the 4 LEP experiments [5]. The consistency, or otherwise, of the indirect and direct limits for m_H constitutes an important test of the SM.

Measurents of the same electroweak observables by different experiments are combined by the LEP-SLD Electroweak Working Group (LSEWWG) [3], but still, in the global fits to the data used to obtain the indirect limit on m_H, a large number of different ''raw'' observables are included in the χ^2. These observables vary widely both in experimental precision and in sensitivity to m_H. They may, however, be further combined, using only very weak theoretical assumptions (lepton universality and the validity of perturbative QED and QCD corrections) to yield a much smaller number of parameters that contain all precise experimental information on m_H. Fitting these parameters to the SM prediction, as is done below, rather than the raw observables, as in the LSEWWG fits, results in much sharper test and, as will be seen, clearly pinpoints possible anomalies or inconstencies in the data. There are essentially four such independent parameters, which may be chosen to be the effective weak coupling constants (vector and axial vector, or right-handed and left-handed) of the charged leptons and b quarks. The effective coupling constants of the other quarks have a similar theoretical status but, because of their much larger experimental errors, have a negligible weight in the determination[1] of m_H. Actually, in the SM, although all four parameters are sensitive to m_t given the present experimental errors, the sensitivity of the b quark couplings to m_H is extremely weak. The method of extraction of the effective coupling constants from the raw observables as been described previously [6–8]. In order to simplify the fitting procedure it is convenient to use, instead of the effective vector (axial vector) coupling constants $\overline{v}_f(\overline{a}_f)(f=l,b)$ the equivalent quantities, with uncorrelated experimental errors, $A_f,\overline{s}_f$ defined by the relations

$$A_f \equiv \frac{2(\sqrt{1-4\mu_f})\overline{r}_f}{1-4\mu_f+(1+2\mu_f)\overline{r}_f^2}, \tag{1}$$

where

$$\overline{r}_f \equiv \overline{v}_f/\overline{a}_f,$$

and

$$\overline{s}_f \equiv (\overline{a}_f)^2(1-6\mu_f)+(\overline{v}_f)^2. \tag{2}$$

The parameter $\mu_f=(\overline{m}_f(M_Z)/M_Z)^2$ where $\overline{m}_f(Q)$ is the running fermion mass at the scale Q, can be set to zero for $f=l$ to sufficient accuracy, while for b quarks $[\overline{m}_b(M_Z)/M_Z]^2=1.0\times10^{-3}$ [9]. The values of $A_l,\overline{s}_l,A_b,\overline{s}_b$ extracted from the most recent compilation of electroweak data [4] are presented in Table I where they are compared with the SM prediction for $m_t=174$ GeV, $m_H=100$ GeV. The SM predictions used here are derived from the ZFITTER5.10 program package [10], which includes the recently calculated $O(g^4m_t^2/M_W^2)$ two-loop corrections [11]. Good agreement is seen for all parameters except A_b, which differs from the SM prediction by 3.0 standard deviations. The

TABLE I. Measured values of A_f and $\overline{s}_f(f=l,b)$ compared to SM predictions for $m_t=174$ GeV, and $m_H=100$ GeV. Dev(σ) $=$(Meas.-SM)/Error.

	Leptons		b quarks	
	A_l	$\overline{s}_l$	A_b	$\overline{s}_b$
Meas.	0.1492(18)	0.25243(30)	0.878(19)	0.3662(14)
SM	0.1467	0.25272	0.9347	0.3647
Dev.(σ)	1.4	−1.0	−3.0	1.1

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[1]Although the direct measurement of the W mass is expected, in the future, to provide valuable information on m_H, the present experimental error is too large to be competitive with Z decay measurements.

TABLE II. SM fits to different data sets. 95% C.L. upper limits for m_H are given in the square brackets.

Fitted Quantities	$\alpha(M_Z)^{-1}$	m_t (GeV)	m_H (GeV)	C.L.(%)
	128.986	171.5±3.8	$73.8^{+46.5}_{-29.4}$ [166]	24
A_l, $\overline{s_l}$, m_t	128.896	170.7±3.8	$38.0^{+30.5}_{-19.8}$ [94]	28
	128.806	172.0±3.8	$19.6^{+18.1}_{-8.0}$ [54]	57
	128.986	171.9±3.6	$124.7^{+58.7}_{-40.9}$ [234]	1.8
A_l, $\overline{s_l}$, A_b, $\overline{s_b}$, m_t	128.896	171.4±3.6	$77.8^{+38.6}_{-26.2}$ [150]	1.7
	128.806	171.3±3.6	$44.1^{+22.5}_{-19.6}$ [87]	1.8

C.L. that all four parameters agree with the SM is only 1.0%(χ^2/DOF=13.2/4). This apparent anomaly was already apparent in the 1996 LSEWWG averages [12], and has been extensively discussed [6,7]. The right-handed (R) and left-handed (L) effective couplings of the b quarks: $\overline{g_b^R}=(\overline{v_b}-\overline{a_b})/2$, $\overline{g_b^L}=(\overline{v_b}+\overline{a_b})/2$ are found to have the values

$$\overline{g_b^R}=0.1050(90), \qquad \overline{g_b^L}=-0.4159(24)$$

as compared with the respective SM predictions of 0.0774 and -0.4208. The largest anomaly is in $\overline{g_b^R}$ (3.1σ) rather than $\overline{g_b^L}$ (2.0σ).

The purpose of this article is twofold: (i) To recall that only one parameter, $\overline{g_b^R}$, among the four that contain all the high precision information on quantum corrections in Z decays shows a large deviation from the SM prediction [6]. (ii) To point out that the values of the limits on m_H depend strongly on inclusion or exclusion of the b quark data. Using only the leptonic data, that agrees well with the SM prediction, leads to significantly lower values of m_H.

The results of SM fits for m_H and m_t to the parameter sets $A_l,\overline{s_l},m_t$ and $A_l,\overline{s_l},A_b,\overline{s_b},m_t$ are presented in Table II. The recent CDF, D0 average [2,4]: $m_t=173.8\pm5.0$ GeV and the fixed value $\alpha_s(M_Z)=0.120$, consistent with the world average 0.118(5) [13,14] is used in the fits. For each parameter set three fits are performed for different values of $\alpha(M_Z)$, corresponding to the experimental value: $\alpha(M_Z)^{-1}=128.896(90)$ [15], and $\pm1\sigma$ variations on the value. The fitted value of m_H is seen to be very sensitive to $\alpha(M_Z)$. All fits give a very stable value of m_t of $\simeq$171.2 with a maximum variation of 0.7 GeV, much smaller than the typical fit error of $\simeq$3.7 GeV. On the other hand, large variations are seen in m_H both as a function of $\alpha(M_Z)$ and on the inclusion or exclusion of the b quark data. For $\alpha(M_Z)^{-1}=128.896$ the fit excluding the b quark data gives $m_H=38.0^{+30.5}_{-19.8}$ and a 95% C.L. upper limit of 94 GeV; including the b quark data gives $m_H=77.8^{+38.6}_{-26.2}$ and an upper limit of 150 GeV. The C.L.'s of the SM fits to the lepton data and m_t are in the range 24%–57%, whereas when the b quark data is included, the C.L.'s drop to only 1.7%–1.8%. The results on the indirect Higgs boson mass limits are summarized in Table III, where the variations due to the experimental error on $\alpha(M_Z)$ and $\pm1\sigma$ variations in the fitted value of m_t are also presented. When the b quark data is included, the "maximum"[2] 95% C.L. upper limit on m_H is found to be 278 GeV, in good agreement with the LSEWWG value of 280 GeV [4]. Excluding the b quark data, which is incompatible, at the 3σ level, with the SM, reduces the fitted value of m_H by a factor two, and lowers the 95% C.L. upper limit by 56 GeV. Taking into acccount the strong dependence of the limit on $\alpha(M_Z)$ and m_t (see Table III), this is still quite consistent with the direct lower limit of 89.9 GeV [5]. It should be stressed that the shift in the value of m_H is generated due to the high sensitivity of A_l via correlations ($A_{FB}^{0,b}=3A_lA_b/4$) and not by any variation in the quantity A_b, which is quite insensitive to m_H. This point is made clear by Fig. 1, which shows a two dimensional plot of the LEP+SLD average value A_l and A_b(SLD). The diagonal band shows the LEP $A_{FB}^{0,b}$ measurement. Also shown are the 68%, 95% and 99%

TABLE III. Summary of SM fit results for m_H. The errors on m_H are, in order: the 1σ fit error, and the changes produced by $\pm1\sigma$ variations in $\alpha(M_Z)^{-1}$ and m_t. The errors on the upper limit are those due to $\pm1\sigma$ variations in $\alpha(M_Z)^{-1}$ and m_t.

Fitted Quantities	m_H (GeV)	95% C.L. upper limit on m_H (GeV)
A_l, $\overline{s_l}$, m_t	$38^{+31+36+17}_{-20-18-9.5}$	94^{+72+34}_{-40-23}
A_l, $\overline{s_l}$, A_b, $\overline{s_b}$, m_t	$78^{+39+47+24}_{-26-34-17}$	150^{+84+44}_{-63-33}

[2]Given by adding linearly the shifts generated by the experimental error on $\alpha(M_Z)$ and the fit error on m_t.

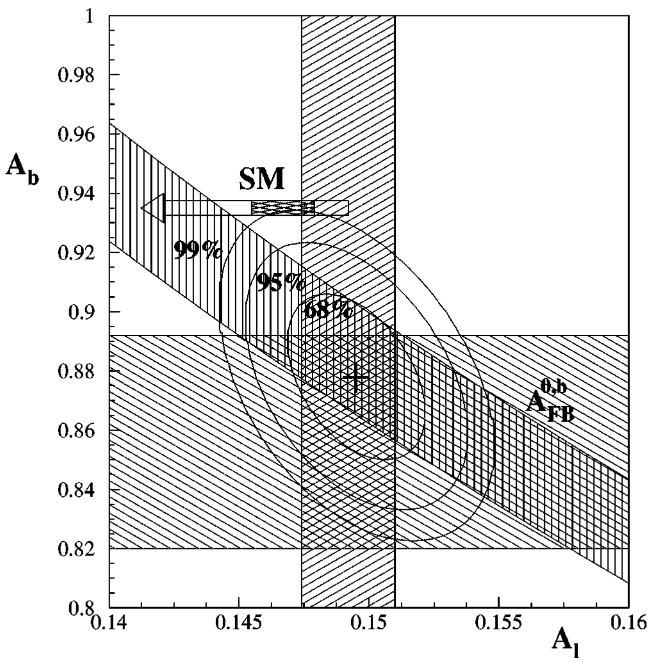

FIG. 1. The cross-hatched bands show the $\pm 1\sigma$ limits for the quantities A_l(LEP+SLD), A_b(SLD), and $A_{FB}^{0,b}$(LEP). The cross shows the best fit to A_l and A_b, togther with 68%, 95% and 99% C.L. contours. The narrow cross hatched rectangle shows the SM prediction for $m_H = 100$ GeV and $m_t = 174 \pm 5$ GeV. The open arrow shows the SM prediction for $m_H = 100^{+200}_{-50}$ GeV and $m_t = 174$ GeV. The arrow points in the direction of increasing m_H.

C.L. contours of the best fit to A_l and A_b using all three data, as well as the prediction of the SM that lies just outside the 99% C.L. contour. The shift towards higher values of m_H caused by the $A_{FB}^{0,b}$ measurement as well as poor agreement of the fit with the SM are evident.

None of the above conclusions were reported when the results of global SM fits by the LSEWWG to the same data set used in this letter, were presented at the recent Vancouver conference [4]. This is because no attempt was made to extract the effective couplings of the b quarks, and the SM fit was performed on a large number (20) of raw electroweak observables, many of which have large errors and/or are relatively insensitive to m_H or the b quark couplings. In fact it is clear from inspection of Fig. 1 that the 3 largest ''pulls''[3] in the global EW fit shown in Ref. [4] [due to A_b(SLD),$A_{FB}^{0,b}$ and $\sin^2\Theta_{eff}^{lept}$ derived from A_{LR}], are all correlated to the large deviation of the best fit value of A_b from the SM prediction. These three data alone contribute 11.1 (or 65%) out of the total χ^2 of 17.0 for 15 DOF. The 3.1σ deviation of $\overline{g_b^R}$ from the SM is not revealed in the SLEWWG fit. Instead smaller deviations appear in the correlated quantities A_b(SLD),$A_{FB}^{0,b}$ and R_b. It is interesting to note that the 17 data whose pulls are least effected by the deviation in the b quark couplings give an anomalously low contribution to the χ^2 (χ^2/DOF=5.9/17, C.L.=99.45%) indicating that, on average, the errors for these quantities may be overestimated by a factor of $\simeq 1.7$. The very low contribution from these data hides the large positive contribution resulting from the deviation in A_b when only the global χ^2 is considered. A similar criticism may be made of another recent global analysis [16] based on the data set used in this paper. In this case the global χ^2 contained 42 data fit to 6 parameters (including m_t and m_H) yielding a χ^2/DOF=28.8/36 (C.L.=80%). It is stated, in consequence, that ''The fit to all precision data is perfect.'' Although it is true that, as in the SLEWWG fit, ''None of the observables deviates from the SM best fit prediction by more than 2 standard deviations'' it also remains true that an anomalously large contribution to the χ^2 comes from the b quark data, where the effective couplings *do deviate from the SM at the* 3σ *level*. This is completely hidden by the good ageement with the SM of 39 out of the 42 data that are fitted.

Finally, it may be mentioned that none of the previous discussions in the literature of the sensitivity of m_H to different data sets [17–19] pointed out either the sensitivity of the limit to the b quark data, or the poor overall confidence levels of SM fits to the effective couplings when the latter are included. A more detailed discussion of this previous literature is given in Ref. [8].

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[3]I.e., (measurement-fit)/error.

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