

# 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  $\approx 2\%$ . Removing the  $b$  quark data improves markedly the quality of the fits and reduces the 95% C.L. upper limit on  $m_H$  by  $\approx 50$  GeV.

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Since the discovery of the top quark by the Collider Detector at Fermilab (CDF) and  $D\bar{O}$  Collaborations [1] and the determination of its mass with a precision of  $\approx 3\%$  [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.

Measurements 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  $\chi^2$ . 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 inconsistencies 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<sup>1</sup> of  $m_H$ . Actually, in the SM, although all four parameters are sensitive to  $m_t$  given the present experimental errors, the sensitiv-

ity 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  $\bar{v}_f(\bar{a}_f)$  ( $f=l,b$ ) the equivalent quantities, with uncorrelated experimental errors,  $A_f, \bar{s}_f$  defined by the relations

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

where

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

and

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

The parameter  $\mu_f = (\bar{m}_f(M_Z)/M_Z)^2$  where  $\bar{m}_f(Q)$  is the running fermion mass at the scale  $Q$ , can be set to zero for  $f=l$  to sufficient accuracy, while for  $b$  quarks  $[\bar{m}_b(M_Z)/M_Z]^2 = 1.0 \times 10^{-3}$  [9]. The values of  $A_l, \bar{s}_l, A_b, \bar{s}_b$  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 ZFIT-TER5.10 program package [10], which includes the recently calculated  $O(g^4 m_t^2/M_W^2)$  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  $\bar{s}_f$  ( $f=l,b$ ) compared to SM predictions for  $m_t = 174$  GeV, and  $m_H = 100$  GeV.  $\text{Dev}(\sigma) = (\text{Meas.} - \text{SM})/\text{Error}$ .

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

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<sup>1</sup>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.(%)
$A_l, \bar{s}_l, m_t$	128.986	$171.5 \pm 3.8$	$73.8^{+46.5}_{-29.4}$ [166]	24
	128.896	$170.7 \pm 3.8$	$38.0^{+30.5}_{-19.8}$ [94]	28
	128.806	$172.0 \pm 3.8$	$19.6^{+18.1}_{-8.0}$ [54]	57
$A_l, \bar{s}_l, A_b, \bar{s}_b, m_t$	128.986	$171.9 \pm 3.6$	$124.7^{+58.7}_{-40.9}$ [234]	1.8
	128.896	$171.4 \pm 3.6$	$77.8^{+38.6}_{-26.2}$ [150]	1.7
	128.806	$171.3 \pm 3.6$	$44.1^{+22.5}_{-19.6}$ [87]	1.8

C.L. that all four parameters agree with the SM is only 1.0% ( $\chi^2/\text{DOF}=13.2/4$ ). 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:  $\bar{g}_b^R = (\bar{v}_b - \bar{a}_b)/2$ ,  $\bar{g}_b^L = (\bar{v}_b + \bar{a}_b)/2$  are found to have the values

$$\bar{g}_b^R = 0.1050(90), \quad \bar{g}_b^L = -0.4159(24)$$

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

The purpose of this article is twofold: (i) To recall that only one parameter,  $\bar{g}_b^R$ , 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  $A_l, \bar{s}_l, m_t$  and  $A_l, \bar{s}_l, A_b, \bar{s}_b, m_t$  are presented in Table II. The recent CDF, D0 average [2,4]:  $m_t = 173.8 \pm 5.0$  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  $\alpha(M_Z)^{-1}$ , corresponding to the experimental value:  $\alpha(M_Z)^{-1} = 128.896(90)$  [15], and  $\pm 1\sigma$  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  $\approx 171.2$  with a maximum variation of 0.7 GeV, much smaller than the typical fit error of  $\approx 3.7$  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  $\pm 1\sigma$  variations in the fitted value of  $m_t$  are also presented. When the  $b$  quark data is included, the ‘‘maximum’’<sup>2</sup> 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  $3\sigma$  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 account 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 ( $A_{FB}^{0,b} = 3A_l A_b / 4$ ) 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  $1\sigma$  fit error, and the changes produced by  $\pm 1\sigma$  variations in  $\alpha(M_Z)^{-1}$  and  $m_t$ . The errors on the upper limit are those due to  $\pm 1\sigma$  variations in  $\alpha(M_Z)^{-1}$  and  $m_t$ .

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

<sup>2</sup>Given by adding linearly the shifts generated by the experimental error on  $\alpha(M_Z)$  and the fit error on  $m_t$ .

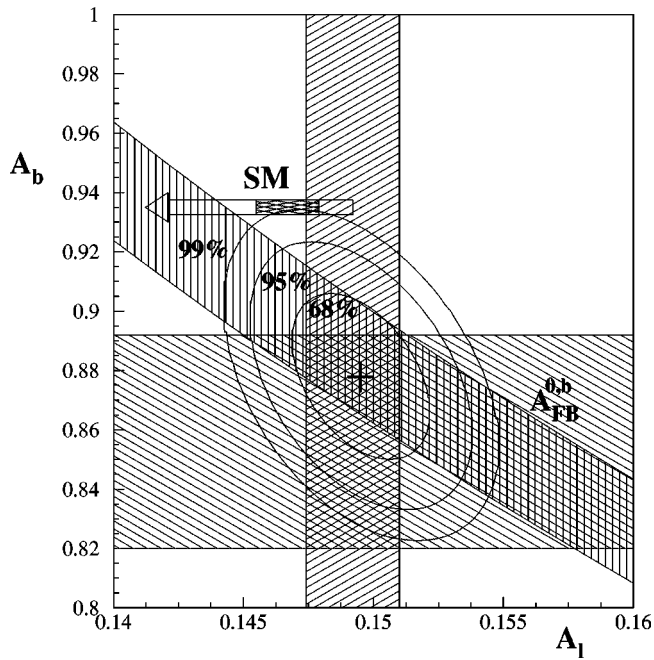


FIG. 1. The cross-hatched bands show the  $\pm 1\sigma$  limits for the quantities  $A_l$ (LEP+SLD),  $A_b$ (SLD), and  $A_{FB}^{0,b}$ (LEP). The cross shows the best fit to  $A_l$  and  $A_b$ , together with 68%, 95% and 99% C.L. contours. The narrow cross hatched rectangle shows the SM prediction for  $m_H=100$  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’’<sup>3</sup> 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  $\chi^2$  of 17.0 for 15 DOF. The  $3.1\sigma$  deviation of  $\bar{g}_b^R$  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  $\chi^2$  ( $\chi^2/\text{DOF}=5.9/17$ , C.L.=99.45%) indicating that, on average, the errors for these quantities may be overestimated by a factor of  $\approx 1.7$ . The very low contribution from these data hides the large positive contribution resulting from the deviation in  $A_b$  when only the global  $\chi^2$  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  $\chi^2$  contained 42 data fit to 6 parameters (including  $m_t$  and  $m_H$ ) yielding a  $\chi^2/\text{DOF}=28.8/36$  (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  $\chi^2$  comes from the  $b$  quark data, where the effective couplings *do deviate from the SM at the  $3\sigma$  level*. This is completely hidden by the good agreement 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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<sup>3</sup>I.e., (measurement-fit)/error.

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