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## Z-DECAYS TO b QUARKS AND THE HIGGS BOSON MASS

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### Abstract

A model independent analysis of the most recent averages of precision electroweak data from LEP and SLD finds a  $3\sigma$  deviation of the parameter  $A_b$  from the Standard Model prediction. The fitted value of  $m_H$  shows a strong dependence on the inclusion or exclusion of b quark data, and the Standard Model fits have poor confidence levels of a few percent when the latter are included. The good fits obtained to lepton data, c quark data and the directly measured top quark mass, give  $m_t = 171.2_{-3.8}^{+3.7}$  GeV and indicate that the Higgs boson mass is most likely less than 200 GeV.

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The dependence of the indirect upper limit on the Higgs boson mass ( $m_H$ ) on the particular choice of high precision electroweak data has been discussed previously in the literature [1, 2], as well as the problem of combining direct and indirect limits on  $m_H$  [3]. It has also recently been noticed that a model independent analysis of Z decay data yields effective b-quark couplings that differ by three standard deviations or more from the predictions of the Standard Electroweak Model (SM) [4, 5]. In this paper a model independent analysis similar to that described in Refs.[4,5] is performed on the latest averages of precision electroweak data [6]. Assuming only lepton universality and the validity of perturbative QED and QCD corrections, several parameters, directly sensitive to electroweak quantum corrections, and so to the mass of the top quark ( $m_t$ ) as well as  $m_H$ , are extracted from the data. The SM predictions, including the recently calculated  $O(g^4 m_t^2/M_W^2)$  two-loop corrections [7] as implemented in the program package ZFITTER5.10 [8] are then fitted to the data to determine indirectly the values of  $m_t$  and  $m_H$ , as well as the overall confidence level (C.L.) for agreement of the fit with the SM.

The six parameters extracted are:  $A_l$ ,  $A_c$ ,  $A_b$ ,  $\bar{s}_l$ ,  $\bar{s}_c$  and  $\bar{s}_b$  where the subscripts  $l$ ,  $c$ , and  $b$  denote charged leptons (assuming universality), c quarks and b quarks respectively. These parameters, equivalent to the effective couplings of leptons, c quarks and b quarks, contain all the high precision information on  $m_t$  and  $m_H$  from Z decay measurements. They are defined, in terms of the effective vector ( $\bar{v}_f$ ) and axial vector ( $\bar{a}_f$ ) coupling constants of the fermion (charged lepton or quark)  $f$ , 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  $f = l, c$  to sufficient accuracy, while for b quarks  $(\bar{m}_b(M_Z)/M_Z)^2 = 1.0 \times 10^{-3}$  [9]. The extraction of  $A_f$  from the various asymmetry and polarisation measurements is straightforward [4, 5]. The quantities  $\bar{s}_f$  are derived, from the measured partial widths, using the relations:

$$\bar{s}_l = (\bar{a}_l)^2 + (\bar{v}_l)^2 = \frac{12\pi\Gamma_l}{\sqrt{2}G_\mu M_Z^3} \frac{1}{(1 + \frac{3\alpha(M_Z)}{4\pi})}, \quad (3)$$

and

$$\bar{s}_Q = \sqrt{\frac{2\pi}{3}} \frac{R_Q \Gamma_Z}{G_\mu M_Z^2} \frac{\sqrt{R_l \sigma_h^0}}{C_{QED}^Q C_{QCD}^Q} \quad (Q = c, b), \quad (4)$$

where

$$C_{QED}^Q = 1 + \frac{3(e_Q)^2}{4\pi}\alpha(M_Z),$$

and

$$C_{QCD}^Q = 1 + C_1^Q\left(\frac{\alpha_s(M_Z)}{\pi}\right) + C_2^Q\left(\frac{\alpha_s(M_Z)}{\pi}\right)^2.$$

The coefficients  $C_1^Q$  and  $C_2^Q$  may be found in Refs.[4,5] to which the reader is referred for all questions of notation. The world average value  $\alpha_s(M_Z) = 0.118(5)$  [10, 11] is used in Eqn.(4). The parameters  $A_f$  (derived from asymmetry or polarisation measurements) and  $\bar{s}_f$  (derived from the partial width of Z decay into  $f\bar{f}$  pairs) have the advantage of uncorrelated experimental errors, thus simplifying the error treatment of the fitting procedure.

The averages of electroweak parameters used in the analysis are presented in Tables 1 and 2<sup>a</sup>. Table 1 contains quantities directly sensitive to  $m_t$  and  $m_H$ , while other essential parameters are found in Table 2.

Before performing any fits to the data, the overall consistency of the different asymmetry and  $\tau$ -polarisation measurements is checked by calculating, in each case, the effective leptonic weak mixing angle<sup>b</sup>:

$$\sin^2 \Theta_{eff}^{lept} = \frac{1 - \bar{r}_l}{4}. \quad (5)$$

The comparison of different measurements of  $\sin^2 \Theta_{eff}^{lept}$  is shown in Fig.1. When measurements of the same quantity by different experiments are in good agreement, as is the case for  $A_{FB}^{0,e}$ ,  $A_{FB}^{0,\mu}$  and  $A_{FB}^{0,\tau}$  the averages over experiments are shown. For the case of  $\tau$ -polarisation, where the consistency of the different experiments is poor [4, 5] the results of the individual LEP experiments are shown. For the purely leptonic measurements (including  $A_{LR}$ ), where only the assumption of lepton universality is needed to extract  $\sin^2 \Theta_{eff}^{lept}$ , the weighted average value of 0.23125(23), (whose  $\pm 1\sigma$  region is indicated by the shaded band in Fig.1) is in good agreement with the individual measurements ( $\chi^2 = 8.1$ , 7 *dof*, C.L. = 0.32). One may note, in particular, the good agreement of the  $A_{LR}$  value with the weighted average. Indeed, only the  $\tau$ -polarisation measurements of DELPHI and OPAL are more than one standard deviation from the average value. Also shown in Fig.1 is the value of  $\sin^2 \Theta_{eff}^{lept}$  derived from  $A_{FB}^{0,b}$ . In this case, besides lepton universality, it is necessary to assume the SM values of the b quark effective couplings. Including this datum in the average gives a somewhat worse consistency  $\chi^2$  ( $\chi^2 = 13.3$ , 8 *dof*, C.L. = 0.10) and changes the weighted average value by  $1.1\sigma$  to 0.23151(20). The deviation of the  $\sin^2 \Theta_{eff}^{lept}$  value derived from  $A_{FB}^{0,b}$  from the leptonic average amounts to  $2.2\sigma$ .

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<sup>a</sup>Unless otherwise stated, all errors quoted are the quadratic sum of the experimental statistical and systematic errors

<sup>b</sup>Note that  $\sin^2 \Theta_{eff}^{lept}$ ,  $\bar{r}_l$  and  $A_l$  are strictly equivalent physical quantities related to each other by one-to-one mappings

The six parameters  $A_f, \bar{s}_f$  ( $f = l, c, b$ ) extracted by the model independent analysis are presented in Table 3, where they are compared with the SM prediction for  $m_t = 174$  GeV and  $m_H = 100$  GeV. All the parameters show good agreement with the SM except for  $A_b$  which lies  $3.0\sigma$  below the expectation. The effective vector and axial-vector coupling constants of leptons, c quarks and b quarks are compared with the SM predictions in Table 4. Both  $\bar{v}_b$  and  $\bar{a}_b$  show deviations of about  $3\sigma$  from the SM; all other couplings are in good agreement. 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:

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

to be compared with the respective SM predictions of 0.0774 and -0.4208, As also observed for the 1996 data averages [4, 5] a somewhat larger deviation ( $3.1\sigma$ ) is seen for  $\bar{g}_b^R$  than for  $\bar{g}_b^L$  ( $2.0\sigma$ ). In Fig.2 are shown the 68%, 95% and 99% C.L. contours of the fit of  $\bar{g}_b^R$  and  $\bar{g}_b^L$  to  $A_b$  and  $\bar{s}_b$ . The SM prediction lies just outside the 99% contour.

Results of SM fits for  $m_t$  and  $m_H$  to different subsets of the data are presented in Table 5 and Fig.3. In the fits the correlations between the errors on  $A_l$  and  $A_Q$ , ( $Q = c, b$ ) derived from the measurements of  $A_{FB}^{0,Q}$ , and those between  $\bar{s}_b$  and  $\bar{s}_c$  are taken into account. The direct SLD measurements of  $A_c, A_b$  give separate uncorrelated<sup>c</sup> contributions to the  $\chi^2$ . The errors on  $m_t, m_H$  quoted in Table 5 are at the  $1\sigma$  level on the individual parameters i.e. one parameter is fixed at the value corresponding to the minimum of the combined fit, the other being varied till  $\chi^2 = \chi_{min}^2 + 1$ . The 95% C.L. upper limits on  $m_H$  are derived from a two-sided 90% confidence interval given by  $\chi^2 < \chi_{min}^2 + 2.7$ . The leptonic data gives a fitted value of  $m_t$  about  $2\sigma$  below the directly measured (CDF and D0) value of  $173.8 \pm 5.0$  GeV [6], and  $m_H = 25.8$  GeV. Adding the c quark data (second row of Table 5) leaves the fitted values of  $m_t$  and  $m_H$  almost unchanged and a good overall fit (C.L.= 56%) is obtained. Combining instead the lepton and b quark data (the third row of Table 5) reduces the fitted value of  $m_t$  by only 3 GeV, but increases the fitted value of  $m_H$  to 42 GeV. This fit has a poor C.L. of only 1.3%, reflecting the large deviation of  $A_b$  from the SM prediction. The results of the fit to all data from Table 3 are given in the last row of Table 5. The fitted value of  $m_t$  is almost the same as for the fit to the lepton and b quark data only,  $m_H$  increases to 45 GeV and the C.L. improves to 3.9%. The 68% C.L. contours in the  $m_H$  versus  $m_t$  plane for the fits to the lepton and c quark data ( second row of Table 5, contour A) and all data ( fourth row of Table 5, contour B) are shown in Fig.3. Also shown in Fig.3 is the current 95% C.L. lower limit on the Higgs boson mass of 89.8 GeV from the direct search results of the four LEP experiments [12], and the directly measured value of  $m_t$ . Inclusion or exclusion of the b quark data has a strong effect on the  $1\sigma$  contour. Indeed, the  $1\sigma$  contour A lies almost entirely within the region for  $m_H$  forbidden at 95% C.L. by the direct search result. Also shown in Table 5 are the results of

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<sup>c</sup>The correlation coefficients between  $A_c, A_{FB}^{0,c}$  and  $A_b, A_{FB}^{0,b}$  are small (0.07,0.03 respectively [15]) and are neglected in the fits

fits to  $m_t$  only, fixing  $m_H$  at 200 GeV. For the fits to the lepton and lepton and c quark data the fitted values of  $m_t$  increase, whereas the C.L.s of the fits decrease, falling to only 2.5% for the lepton data. A similar behaviour is seen in the fits to lepton and b quark data and all data, however the already poor C.L.s of the fits with  $m_t$  and  $m_H$  free become even worse: 0.3% and 2.0% respectively.

All the fits with  $m_t$  and  $m_H$  free shown in Table 5 give values of  $m_t$  about 10 GeV below the directly measured value. Also all the 95% C.L. upper limits on  $m_H$  calculated as described above and shown in Table 5, are less than 90 GeV and so are only marginally consistent with the direct lower limit. However, the  $m_H$  limits also depend strongly on the value of  $\alpha(M_Z)$ . In order to take into account all available experimental information, the fits to the lepton and c quark data and all data are repeated including also in the definition of  $\chi^2$  the directly measured value:  $m_t = 173.8 \pm 5.0$  GeV [6]. The fits are also repeated with  $\pm 1\sigma$  variations in the value of  $\alpha(M_Z)$ . The results of these fits are presented in Table 6.

A very stable value of  $m_t$  of  $m_t = 171 \pm 1$  GeV, consistent with the directly measured value, is found for all six fits. The 95% C.L. upper limits on  $m_H$  are found to be  $105^{+70}_{-46} \text{ } ^{+36}_{-25}$  GeV for leptons and c quarks only, and  $156^{+84}_{-64} \text{ } ^{+44}_{-33}$  GeV for all data. The quoted errors on the limits correspond, respectively, to  $\mp 1\sigma$  variations of  $\alpha(M_Z)$  about the value quoted in Table 2, and  $\pm 1\sigma$  variations of  $m_t$  about the fitted values shown in Table 6. The ‘maximal’<sup>d</sup> value of 284 GeV, in the case the b quark data is included, agrees well with the 95% C.L. upper limit of 280 GeV from the CERN Electroweak Working Group quoted in Ref.[6]. The corresponding maximal value for leptons and c quarks only is 211 GeV. It is clear from Table 6 that consistency with the direct lower limit on  $m_H$  strongly disfavours values of  $\alpha(M_Z)$  near to the  $+1\sigma$  experimental limit. The sensitivity of Higgs mass limits to inclusion or exclusion of the b quark data is evident from the fits shown in Tables 5 and 6. Inclusion of the b quark data raises the 95% C.L. from  $\simeq 105$  GeV to  $\simeq 156$  GeV for  $\alpha(M_Z)^{-1} = 128.896$ . However, the quality of the SM fits is then poor with C.L.s of only a few %. A careful examination of the ‘pulls’( datum - best fit value) of the fits shows that, although the shift in  $m_H$  is entirely due to the deviation in  $A_b$ , the bias is actually produced by variation of the parameter  $A_l$  (very sensitive to  $m_H$ ), rather than  $A_b$  (completely insensitive to  $m_H$  with the present experimental errors). The measured quantity  $A_{FB}^{0,b} = 3A_l A_b / 4$  lies below the SM value corresponding to the purely leptonic data due to the low value of  $A_b$ . This deviation is reduced in the fit by increasing  $m_H$  so that  $A_l$  is reduced.  $A_b$  itself is essentially unchanged by the variation in  $m_H$ . However, the leptonic data strongly constrains the possible downward variation of  $A_l$ . This explains both the large ‘ $2\sigma$ ’ ‘pulls’ observed for the 3 quantities  $A_b$ ,  $A_{FB}^{0,b}$  and  $\sin^2 \theta_{eff}^{lept}$  from  $A_{LR}$  in the global fit shown in Ref.[6] and the poor confidence levels of all the fits including b quark data shown in Tables 5 and 6.

The previous papers discussing the sensitivity of the indirect limit on  $m_H$  to the data from different electroweak measurements focussed on the apparent

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<sup>d</sup>i.e. the value obtained by adding linearly the  $+1\sigma$  errors due to  $\alpha(M_Z)^{-1}$  and  $m_t$ .

incompatibility of  $\sin^2 \Theta_{eff}^{lept}$  derived from the SLD  $A_{LR}$  measurement, both with the other LEP measurements and the direct LEP lower limit on  $m_H$ . The analysis of the authors of Ref.[2], based on the data available at the end of 1995 [14] also considered the effect of  $R_b$ , which, at that time, differed from the SM prediction by about  $3\sigma$ . Gurtu [1], using the same 1996 data set [15] as in the previous model independent analysis [4, 5] of the present author, concluded that the  $A_{LR}$  measurement must either have been subject to a very large statistical fluctuation, or an unknown systematic error which was then treated by the Particle Data Group rescaling procedure [16]. Actually, a more careful examination of the data [4, 5] shows that the situation for the 1996 data was quite similar to that of the current data <sup>e</sup> shown in Fig.1. In fact the values of  $\sin^2 \Theta_{eff}^{lept}$  derived from  $A_{LR}$ ,  $A_{FB}^{0,e}$ ,  $A_{FB}^{0,\mu}$ ,  $A_{FB}^{0,\tau}$  and the L3  $\tau$ -polarisation measurement of  $A_l$  were all consistent. On the other hand, systematically higher values were given by the  $\tau$ -polarisation measurements of ALEPH, DELPHI and OPAL and by the precise  $A_{FB}^{0,b}$  measurement, on the assumption of SM values for the b quark couplings. This consistency of the majority of the determinations of  $\sin^2 \Theta_{eff}^{lept}$  (including  $A_{LR}$ ) was obscured by the ordering of the data in the cumulative averages of  $\sin^2 \Theta_{eff}^{lept}$  shown in Fig.5 of Ref.[1]. If  $A_{FB}^{0,b}$  had been the last datum to be included instead of  $A_{LR}$ , the former not the latter would apparently have given the largest single contribution to the  $\chi^2$ . The model independent analysis of Refs.[4,5] showed that, indeed, it is in the b quark couplings that the largest apparent deviation from the SM predictions are found. Repeating the analysis described above for the data set of Ref.[15] leads to 95% C.L. upper limits on  $m_H$  of  $101_{-43}^{+77} \text{ }_{-25}^{+48}$  GeV or  $220_{-92}^{+114} \text{ }_{-52}^{+71}$  GeV when the b quark data are, respectively, excluded or included. These limits may be compared with the C.L., based on the maximum of the  $1\sigma$  contour in the  $m_t$  versus  $m_H$  plane ( after rescaling the errors according to the PDG recipe of Ref.[16]), of 650 GeV, quoted in Ref.[1]. The limit similarly defined from the  $1\sigma$  contour of the fit to the 1996 data, similar to that presented in the fifth row of Table 6, is much lower, 249 GeV. Also the ‘maximal’ 95% C.L., calculated as described above, but using all the corresponding 1996 data is only 405 GeV.

Neither Ref.[1] nor the more recent papers of Chanowitz [3] discuss either the sensitivity of the Higgs mass limits to the b decay data or *the goodness of fit of the SM to the subsets of data directly sensitive to  $m_t$  and  $m_H$* . The  $\chi^2$  quoted for the fit to all data of Ref.[1] was 19 for 14 *dof* (C.L.=0.17). However, of this  $\chi^2$ , 9.9 (i.e. 52%) is contributed by only three data:  $R_b$ ,  $A_{FB}^{0,b}$  from LEP and  $A_b$  from SLD, just those that are directly sensitive to the b quark couplings. <sup>f</sup> The C.L. of a  $\chi^2$  of 9.9 for 3*dof* is only 0.02. In

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<sup>e</sup>The values of  $\sin^2 \Theta_{eff}^{lept}$  derived from  $A_{LR}$  and  $A_{FB}^{0,b}$  in 1996 were 0.23060(48) and 0.23247(43) respectively; they differ by  $2.9\sigma$ . The corresponding numbers for 1998 are 0.23101(31) and 0.23223(38) respectively, with a difference of  $2.5\sigma$ . The shifts are  $+0.9\sigma$  and  $-0.6\sigma$  respectively. The largest change from a single experiment between 1996 and 1998 occurs in the ALEPH  $\tau$ -polarisation value of  $\sin^2 \Theta_{eff}^{lept}$  which changes from 0.2333(14) to 0.23146(58), a  $-1.3\sigma$  shift. The overall consistency C.L. of the leptonic data shown in Fig.1. improves from 8.2% to 32% between 1996 and 1998

<sup>f</sup>The situation is similar for the fit to the most recent data [6]. The same three data contribute 8.7 out of a total  $\chi^2$  of 16.4

fact, the fits of Ref.[1] include many data that are quite insensitive to  $m_t$  and  $m_H$ . The poor quality of the SM fit to the extracted effective couplings due to the apparently anomalous values for the b quarks <sup>g</sup> was first pointed out in Refs.[4,5].

There are three possible causes of the apparent deviation of the b quark couplings from the SM predictions: (i) a statistical fluctuation, (ii) a hitherto unknown systematic error in the LEP  $A_{FB}^{0,b}$  and SLD  $A_b$  measurements, (iii) new physics, beyond the SM, in b decays. For example, the deviations of the  $\sin^2 \theta_{eff}^{lept}$  values derived from  $A_{FB}^{0,b}$  and some tau-polarisation measurements from those derived from purely leptonic observables (see Fig 1) has been conjectured to arise from poorly understood hadronisation effects [19]. A ‘new physics’ scenario has been proposed [20] that explains the anomalous b quark couplings while leaving unchanged the Standard Model  $m_H$  dependence of the leptonic effective couplings.

It can be seen from Table 3 that all the apparent deviation is in the single parameter  $A_b$ . The parameter  $\bar{s}_b$  (derived from  $R_b$ ) differs from the SM expectation by only  $1.1\sigma$ . This good agreement of  $\bar{s}_b$  is highly non-trivial in the SM due to the large flavour specific and  $m_t$  dependent vertex corrections in Z decays to b quarks. Removing these corrections results in a predicted value of  $\bar{s}_b$  of 0.370, which differs by  $2.7\sigma$  from the measured value quoted in Table 3. It seems unlikely that the good agreement observed for  $\bar{s}_b$  with the SM prediction is a lucky accident, as must be the case if there is indeed a new physics explanation of the measured values of  $\bar{a}_b$  and  $\bar{v}_b$  shown in Table 4. This argument disfavors the explanation (iii) and favours (i) or (ii) (or some combination of the two).

Assuming gaussian errors, the probability that one of the six parameters in Table 3 shows a deviation from the SM prediction of  $3\sigma$ , or greater, is 1.6%. In order to obtain a value of  $\sin^2 \Theta_{eff}^{lept}$  equal to the weighted average of the leptonic measurements shown in Fig. 1, the value of  $A_{FB}^{0,b}$  must be increased by 5.5%, as compared to the estimated fractional systematic error on  $A_{FB}^{0,b}$  of 1.0%. There is a correction of  $\simeq 1.9\%$  to the raw measured value of  $A_{FB}^{0,b}$  to account for QCD effects [21]. To explain the observed deviation of  $\sin^2 \Theta_{eff}^{lept}$  as a QCD effect, an extra correction of 3.6%, would be needed as compared to the estimated systematic error on the QCD correction of only 0.3%.

Independently of the explanations (i),(ii),(iii) of the apparently anomalous b quark couplings, the upper limit on the Higgs boson mass is expected, in all cases, be lower than those hitherto quoted [1, 6, 14, 15, 22] derived from fits including the b quark data. In cases (i) and (ii), the true value of  $\sin^2 \Theta_{eff}^{lept}$  should be consistent with the average of the leptonic data shown in Fig 1, leading to a limit similar to those found in the lepton and lepton + c quark fits shown in Tables 5 and 6. In case (iii), where the SM breaks down for the b quark couplings, the latter can give no information whatever <sup>h</sup> on the Higgs

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<sup>g</sup>The large deviations of the b quark couplings from the SM predictions have also been reported, but not discussed in detail, by Renton [17] and Grant and Takeuchi [18]

<sup>h</sup>As pointed out above, also in the case that the SM is respected, the b quark effective couplings have only a very weak sensitivity to  $m_H$ .

mass, so, assuming the SM does apply to the lepton and c quark data (as is the case for the model described in Reference[20]), the same conclusion is drawn about the Higgs mass limit. Actually, the largest uncertainty on the limit is currently due to the errors of the  $\alpha(M_Z)$  determination. Using instead of the value quoted in Table 2, derived from Ref.[23], the more recent, but model dependent, determination of Ref.[24] of  $\alpha(M_Z)^{-1} = 128.923(36)$  leads to the tighter 95% C.L. upper bounds on  $m_H$  of  $121_{-23}^{+31} \text{ }_{-29}^{+42}$  GeV ( $176_{-30}^{+37} \text{ }_{-38}^{+49}$  GeV) in the case that the b quark data is excluded (included).

In conclusion, it may be stated that in view of the still large uncertainties on the upper bound on  $m_H$  due to the experimental errors on  $\alpha(M_Z)$  and  $m_t$  there is no conflict with the current 95% C.L. lower limit of 89.8 GeV on the  $m_H$  [13]. However, independently of the interpretation given to the apparent anomalies in the b quark couplings, the most recent data indicates that the mass of the Higgs boson, if it exists, is probably less than 200 GeV.

After completion of the first version of this paper several other global analyses of the same data set have been performed [25, 26, 27]. Erler and Langacker [25] did discuss the  $3\sigma$  deviation in the LEP+SLD average value of  $A_b$ . However, the effective couplings of the heavy quarks were not extracted, and, on the basis of the good  $\chi^2$  of a global fit to a total of 42 data, they concluded that ‘the fit to all precision data is perfect’. They did not notice, that as pointed out in this paper, a fit to the effective couplings alone ( although the ‘information content’ concerning  $m_t$  and  $m_H$  is essentially equivalent to the data used in their fit), gives only poor agreement with the SM. The effect of the apparent  $A_b$  anomaly on the  $\chi^2$  of their global fit is masked by the contributions of many data that have large errors and/or are relatively insensitive to  $m_t$  and  $m_H$ . Neubert [25] mentioned the  $A_b$  deviation, and although discussing the sensitivity of  $m_H$  to different measurements, did not point out in the text the strong sensitivity to  $A_{FB}^{0,b}$ . As shown in the present paper, this increases the fitted value of  $m_H$ , even though, in the SM, the effective b quark couplings are quite insensitive to  $m_H$ . In fact, inspection of Fig.5. of [25] shows clearly that the determination of  $m_H$  from  $A_{FB}^{0,b}$  alone is strongly biased towards high values. This however was not remarked, and the author concluded, instead, that ‘there is no particular set of measurements that pulls  $m_H$  down’. Renton [27] specifically discussed the apparent anomaly in the b quark data and extracted the effective couplings, finding results in good agreement with those quoted in Table 4 above. The sensitivity of the Higgs mass to inclusion or exclusion of the the b quark data was also studied and results consistent with those shown in the present paper obtained.

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LEP						
leptons			c quarks		b quarks	
$A_{FB}^{0,l}$	$A_l$ ( $\tau$ poln.)	$\Gamma_l$ (MeV)	$A_{FB}^{0,c}$	$R_c$	$A_{FB}^{0,b}$	$R_b$
0.01683(96)	0.1452(34)	83.90(10)	0.0714(44)	0.1733(44)	0.0991(21)	0.21656(74)
SLD						
leptons		c quarks		b quarks		
$A_{LR}$		$A_c$		$A_b$		
0.1511(24)		0.638(40)		0.856(36)		

Table 1: Average values of electroweak observables [6] directly sensitive to  $m_H$  and  $m_t$  used in the analysis. The SLD measurements of  $R_c$  and  $R_b$  are included in the ‘LEP’ averages shown

$M_Z$ GeV	$\Gamma_Z$ (GeV)	$\sigma_h^0$ (nb)	$R_l$	$\alpha(M_Z)^{-1}$	$G_\mu$ (GeV $^{-2}$ )
91.1867(21)	2.4939(24)	41.491(58)	20.765(26)	128.896(90)	$1.16639(1) \times 10^{-5}$

Table 2: Other electroweak parameters used in the analysis [6, 12].

	leptons		c quarks		b quarks	
	$A_l$	$\bar{s}_l$	$A_c$	$\bar{s}_c$	$A_b$	$\bar{s}_b$
Meas.	0.1492(18)	0.25243(30)	0.638(28)	0.2950(74)	0.878(19)	0.3662(14)
SM	0.1467	0.25272	0.6677	0.2882	0.9347	0.3647
Dev.( $\sigma$ )	1.4	-1.0	-1.1	0.92	-3.0	1.1

Table 3: Measured values of  $A_f$  and  $\bar{s}_f$  compared to SM predictions for  $m_t = 174$  GeV,  $m_H = 100$  GeV. Dev( $\sigma$ ) = (Meas.-SM)/Error.

	leptons		c quarks		b quarks	
	$\bar{a}_l$	$\bar{v}_l$	$\bar{a}_c$	$\bar{v}_c$	$\bar{a}_b$	$\bar{v}_b$
Meas.	-0.50102(30)	-0.03759(46)	0.511(7)	0.184(10)	-0.5208(66)	-0.311(11)
SM	-0.50136	-0.03697	0.501	0.191	-0.4981	-0.3434
Dev.( $\sigma$ )	1.1	-1.3	1.4	-0.7	-3.4	2.9

Table 4: Measured values of effective coupling constants compared to SM predictions for  $m_t = 174$  GeV,  $m_H = 100$  GeV. Dev( $\sigma$ ) = (Meas.-SM)/Error.

Fitted Quantities	$m_H$ free			$m_H = 200$ GeV	
	$m_t$ (GeV)	$m_H$ (GeV)	C.L.(%)	$m_t$ (GeV)	C.L.(%)
$A_l, \bar{s}_l$	$164.6^{+5.8}_{-6.2}$	$25.8^{+20.5}_{-10.9}$ [63]	100	$184.8^{+5.4}_{-5.5}$	2.5
$A_l, \bar{s}_l, A_c, \bar{s}_c$	$164.4^{+5.9}_{-6.1}$	$28.2^{+20.8}_{-12.0}$ [66]	56	$184.5^{+5.3}_{-5.5}$	16
$A_l, \bar{s}_l, A_b, \bar{s}_b$	$161.5^{+5.5}_{-5.7}$	$41.9^{+19.8}_{-16.6}$ [79]	1.3	$180.8^{+5.0}_{-5.1}$	0.3
$A_l, \bar{s}_l, A_c, \bar{s}_c, A_b, \bar{s}_b$	$161.6^{+5.4}_{-5.6}$	$45.1^{+20.5}_{-16.8}$ [83]	3.9	$180.4^{+4.9}_{-5.0}$	2.0

Table 5: SM fits to different data sets. 95% C.L. upper limits for  $m_H$  are given in square brackets.

Fitted Quantities	$\alpha(M_Z)^{-1}$	$m_t$ (GeV)	$m_H$ (GeV)	C.L.(%)
$A_l, \bar{s}_l, A_c, \bar{s}_c, m_t$	128.986	$171.7^{+3.7}_{-3.8}$	$81.6^{+48.8}_{-31.6}$ [175]	51
	128.896	$171.2^{+3.7}_{-3.8}$	$47.2^{+29.8}_{-24.5}$ [105]	53
	128.806	$171.8^{+3.7}_{-3.8}$	$21.7^{+20.1}_{-9.1}$ [59]	65
$A_l, \bar{s}_l, A_c, \bar{s}_c, A_b, \bar{s}_b, m_t$	128.986	$171.9 \pm 3.6$	$131.3^{+58.9}_{-41.6}$ [240]	4.5
	128.896	$171.5 \pm 3.6$	$83.3^{+39.1}_{-27.1}$ [156]	4.3
	128.806	$171.4 \pm 3.6$	$47.9^{+23.2}_{-19.3}$ [92]	4.4

Table 6: SM fits to different data sets. 95% C.L. upper limits for  $m_H$  are given in square brackets.

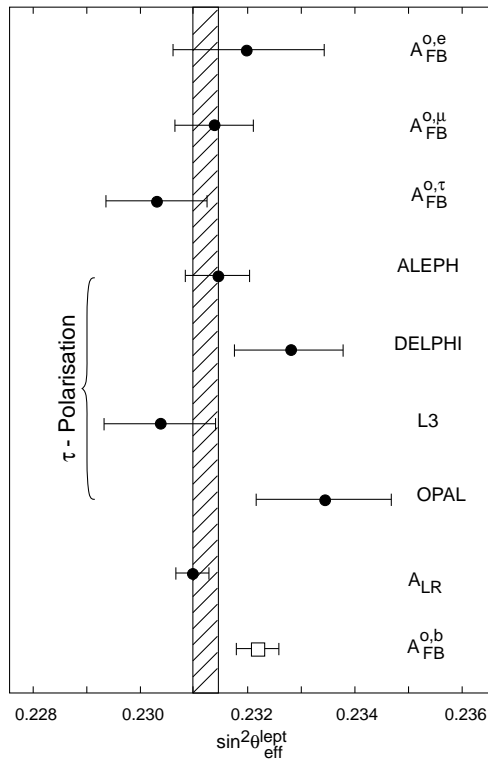


Figure 1: Values of  $\sin^2 \Theta_{eff}^{lept}$  calculated using different electroweak observables. The cross-hatched band shows the  $\pm 1\sigma$  region of the weighted average of the leptonic measurements (solid circles). The value derived from  $A_{FB}^{0,b}$  (open square) assuming SM values for the b quark couplings and not included in the weighted average, is shown for comparison.

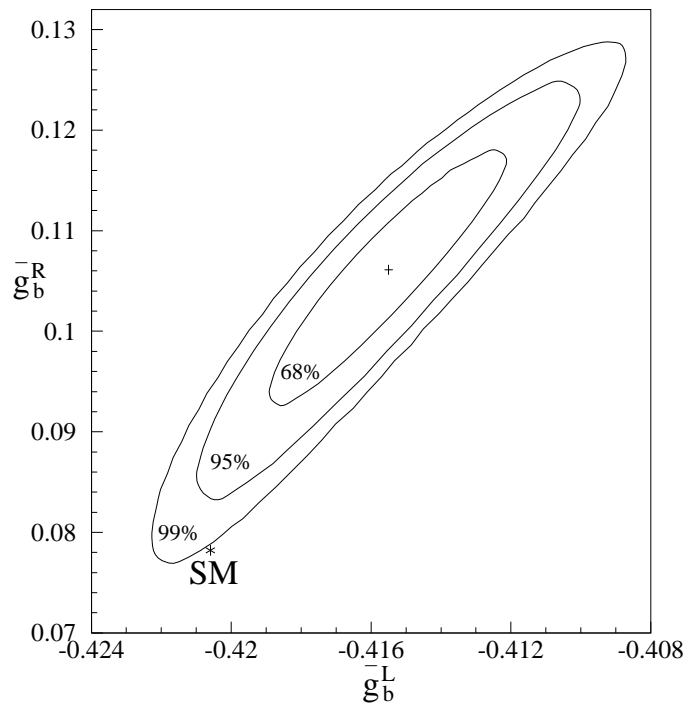


Figure 2: Contour plot for fit to  $\bar{g}_b^L$  and  $\bar{g}_b^R$ . The 68%, 95% and 99% C.L. contours are shown. The SM prediction is for  $m_t = 174$  GeV,  $m_H = 100$  GeV.

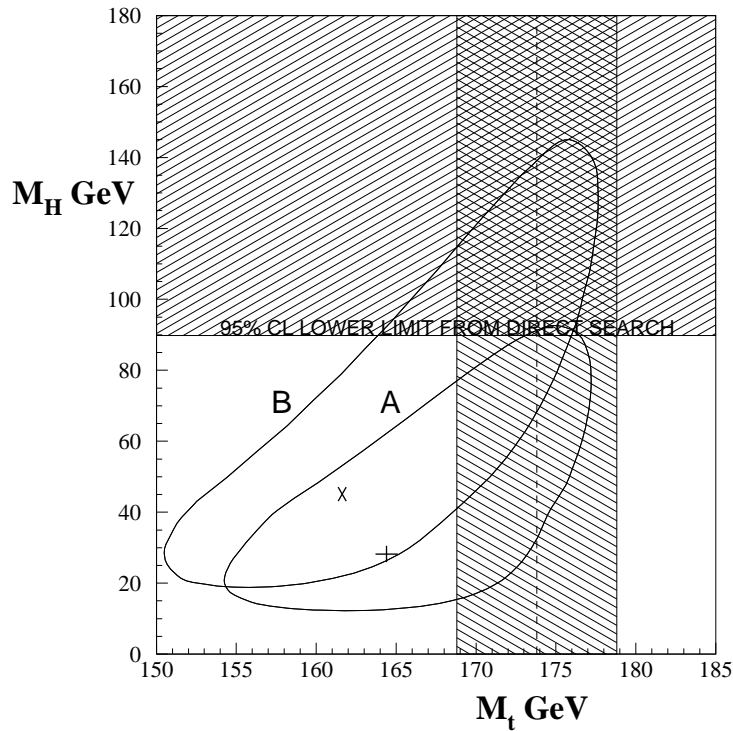


Figure 3: Contour plot for fit to  $m_t$  and  $m_H$ . Contours at the 68% C.L. are shown for fits to the lepton and c quark data only (Contour A, best fit position +) and to lepton, c quark and b quark data (Contour B, best fit position  $\times$ ). The cross hatched areas show the allowed regions for the direct Higgs search [13] and the direct measurement:  $m_t = 173.8 \pm 5.0$  GeV [6]. These limits are shown for comparison only, and are not included in the fits.