

# Are there anomalous Z fermion couplings?

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**Abstract.** The couplings of the fermions to the Z boson are of great importance in establishing the validity of the Standard Model and in looking for physics beyond it. The couplings of the b-quark to the Z boson have been the subject of much experimental study and theoretical interpretation. The apparent excess in the value of  $R_b^0$ , the ratio of the partial width of the Z boson to  $b\bar{b}$  to its total hadronic width, above the Standard Model expectation reported a few years ago has now become much less significant. However, the measurements of the pole forward-backward asymmetry  $A_{\text{FB}}^{0,b}$  for b-quarks at the Z pole and of the *polarisation parameter*  $A_b$ , obtained using a polarised electron beam, have improved considerably in accuracy. The latest data are examined and values of the vector and axial-vector b-quark and c-quark couplings to the Z are extracted. The left and right handed couplings are also extracted. It is found that whereas the c-quark couplings are compatible with the Standard Model, those of the b-quark data are only compatible with the Standard Model at about the 1% level. In addition, the individual lepton couplings are extracted and the degree to which the data support the hypothesis of *lepton universality* is discussed. The sensitivity of the limits from electroweak fits to the Higgs boson mass to these data is examined.

## 1 Introduction

The couplings of leptons and quarks to the Z boson are of fundamental importance both in testing the Standard Model (SM) and in searching for, or setting limits on, physics beyond the SM.

The results available in the Summer of 1995 [1] showed some possibly significant differences from the SM expectations in the values of  $R_b^0$  and  $R_c^0$ ; where  $R_q^0$  is the ratio of the Z partial width to  $q\bar{q}$  to the total hadronic width. These were about 3.1 and 2.4 standard deviations above and below the SM values for  $R_b^0$  and  $R_c^0$  respectively.

The  $Zb\bar{b}$  vertex is a sensitive probe for new physics arising from vertex corrections. The above results, in particular those for  $R_b^0$ , gave rise to considerable theoretical speculation on possible physics beyond the SM which could lead to such an increase. Within the context of Supersymmetry a possible explanation was the existence of light Supersymmetric particles (charginos, top-squarks), which could suitably enhance  $R_b^0$ . However, the apparently low value for  $R_c^0$  did not seem to have a straightforward interpretation.

Since that time the data samples of Z bosons analysed, both at the CERN LEP accelerator and at the SLC, have considerably increased. The experimental techniques used in b and c-tagging have also improved significantly due to the advent of improved Microvertex Detectors and the implementation of new tags, in particular mass tags. The measurements of the forward-backward asymmetry  $A_{\text{FB}}^{0,b}$  for b-quarks at the Z pole and of the *polarisation parameter*  $A_b$ , obtained using a polarised electron beam, have improved considerably in accuracy.

The latest, but still largely preliminary, data are examined and values of the vector and axial-vector couplings to the Z of the three lepton species, and also of b and c quarks, are simultaneously extracted. The left and right handed heavy quark couplings are also extracted. The degree to which the data support the hypothesis of *lepton universality* is examined. All of these couplings are compared to those expected in the Standard Model.

One important aspect of precision electroweak fits is on the constraints the data give on the Standard Model Higgs boson. The sensitivity of the limits from electroweak fits to the Higgs boson mass to the most sensitive data is examined. In these fits the precise value of the top-quark mass  $m_t = 173.8 \pm 5.0$  GeV measured at Fermilab by the CDF and D0 experiments[2] is a very important constraint.

## 2 Z boson couplings

The couplings of a fermion f to the Z boson are specified by its effective vector and axial-vector couplings  $v_f$  and  $a_f$  respectively. A useful quantity is the *coupling* or *polarisation parameter* for fermion f

$$A_f = \frac{2v_f a_f}{v_f^2 + a_f^2}. \quad (1)$$

The pole forward-backward asymmetry of fermion f is given by

$$A_{\text{FB}}^{0,f} = \frac{3}{4} A_e A_f. \quad (2)$$

Since  $A_f$  depends on the ratio  $v_f/a_f$ , a measurement of  $A_{\text{FB}}^{0,f}$  depends on both  $v_e/a_e$  and  $v_f/a_f$ . The effective couplings can also be written as

$$a_f = I_f^3 \sqrt{\rho_f}, \quad \frac{v_f}{a_f} = 1 - 4|Q_f| \sin^2 \theta_{\text{eff}}^f, \quad (3)$$

where the mixing angle defined for *leptons* ( $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ ) is used for reference. Those defined for quarks have small shifts, due to SM plus any new physics [3]. The Z partial decay width to  $f\bar{f}$  is  $\Gamma_f \sim (v_f^2 + a_f^2)$ .<sup>1</sup>

The results of measurements of the  $\tau$  polarisation are very sensitive to the lepton couplings. The average  $\tau$  polarisation gives  $\mathcal{A}_\tau$  and the forward-backward asymmetry gives  $\mathcal{A}_e$ . The correlation between these quantities is negligible.

The results of the hadronic and leptonic cross-sections and the leptonic forward-backward asymmetries are expressed in terms of the five parameters: the mass and width of the Z boson  $M_Z$  and  $\Gamma_Z$ , the hadronic pole cross-section  $\sigma_h^0 = 12\pi\Gamma_e\Gamma_{\text{had}}/(M_Z^2\Gamma_Z^2)$ , the ratio of the hadronic to leptonic widths  $R_\ell = \Gamma_{\text{had}}/\Gamma_l$  and the pole forward-backward asymmetry for leptons  $A_{\text{FB}}^{0,\ell}$ . These are chosen to be largely uncorrelated experimentally. A more detailed discussion of the variables and their definitions can be found in [4]. The five parameter formalism assumes *lepton universality*. If this hypothesis is not imposed then the results are given separately for  $R_\ell$  and  $A_{\text{FB}}^{0,\ell}$  for each lepton species; a total of nine parameters.

The above quantities have been accurately determined by the LEP experiments using the large statistics gathered at, or close to, the Z peak. At the SLC the polarised electron beam gives additional information on the couplings from a measurement of

$$A_{\text{LR}} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e, \quad (4)$$

where  $\sigma_L(\sigma_R)$  is the total cross-section for a left (right) handed polarised incident electron beam. This measurement is inclusive to any Z final state. If the forward-backward asymmetry for a fermion f is also measured for the two polarisation states, giving the left-right forward-backward asymmetry  $\hat{A}_{\text{FB}}$ , then the coupling  $A_f$  can be directly extracted. Measurements of all these quantities have been performed by the SLD Collaboration.

All of these results can be combined and values of the individual couplings of the leptons and b and c quarks to the Z can be extracted. The SLD results give directly  $\mathcal{A}_e$ ,  $\mathcal{A}_b$  and  $\mathcal{A}_c$ ; thus giving the ratios of the vector to axial-vector couplings without the use of other data. The  $\tau$  polarisation gives directly values of  $\mathcal{A}_e$  and  $\mathcal{A}_\tau$ . The forward-backward asymmetries obtained using unpolarised beams give the product of  $\mathcal{A}_e$  and  $A_f$ , so the extracted values of  $\mathcal{A}_b$  and  $\mathcal{A}_c$  depend on  $\mathcal{A}_e$ .

<sup>1</sup> In addition there is a much smaller term proportional to  $(v_f^2 - a_f^2)m_f^2/M_Z^2$ . This is taken into account in the fits discussed here.

**Table 1.** Results of the data on Z couplings used in the fits. For the Z lineshape data the  $\chi^2/\text{df}$  of the average is 28/27, a probability of 41%. For the heavy flavour data the  $\chi^2/\text{df}$  of the average is 44.1/(88-13), a probability of more than 99%. If lepton universality is imposed then  $R_\ell = 20.765 \pm 0.026$  and  $A_{\text{FB}}^{0,\ell} = 0.01683 \pm 0.00096$

quantity	value	error
Z lineshape		
$M_Z(\text{GeV})$	91.1867	0.0021
$\Gamma_Z(\text{GeV})$	2.4939	0.0024
$\sigma_h^0(\text{nb})$	41.491	0.058
$R_e$	20.783	0.052
$R_\mu$	20.789	0.034
$R_\tau$	20.764	0.045
$A_{\text{FB}}^{0,e}$	0.0153	0.0025
$A_{\text{FB}}^{0,\tau}$	0.0183	0.0017
$\tau$ polarisation		
$\mathcal{A}_\tau$	0.1431	0.0045
$\mathcal{A}_e$	0.1479	0.0051
SLD $A_{\text{LR}}$		
$A_{\text{LR}}$	0.15042	0.00228
heavy flavour		
$R_b^0$	0.21656	0.00074
$R_c^0$	0.1735	0.0044
$A_{\text{FB}}^{0,b}$	0.0990	0.0021
$A_{\text{FB}}^{0,c}$	0.0709	0.0044
$\mathcal{A}_b$	0.867	0.035
$\mathcal{A}_c$	0.647	0.040

### 3 Results on Z boson couplings

The data used in the fits described below are mostly those presented at ICHEP 98. The Z lineshape[5],  $\tau$  polarisation[6], LEP heavy flavour[7,8] and SLD results on  $A_{\text{LR}}$  and heavy flavour[9,10] data have been combined using the standard procedures of the LEP Electroweak Working Group (see [11,12]). Some of the numbers have been modified since the presentations at the conference, so the actual values used are given in Table 1. More details and the correlation matrices used can be found in [13]. Many of the data are still preliminary.

All of the LEP 1 data have been used for the lineshape averages. For the  $\tau$ -polarisation the complete LEP 1 data sets for ALEPH and DELPHI were added to that of L3 for ICHEP 98. The OPAL data set does not yet include the 1995 data. The SLD  $A_{\text{LR}}$  measurement includes the latest data taken in 1998. The heavy flavour data do not yet contain all of the possible LEP 1 data. However, for  $R_b^0$  most of the potential data are now used.

It can be noted that the value of  $\mathcal{A}_e$  from  $A_{\text{LR}}$  is compatible with the less precise value of  $\mathcal{A}_e$  from  $\tau$ -polarisation at the  $0.5\sigma$  level, and at the  $1.3\sigma$  level compared to the value of  $\mathcal{A}_e$  from  $\tau$ -polarisation if lepton-universality is assumed ( $\mathcal{A}_e = 0.1452 \pm 0.0034$ ). The  $A_{\text{LR}}$  result is also

compatible with the value  $A_e = 0.1498 \pm 0.0043$  from  $A_{\text{FB}}^{0,\ell}$  (assuming lepton universality) at the  $0.1\sigma$  level.

## 4 Extraction of fermion couplings

A simultaneous fit is made to the data discussed above in order to extract both the lepton and heavy quark vector and axial-vector couplings<sup>2</sup>. The measurements used are the 9 parameter lineshape results (which reduces to 5 parameters if lepton universality is imposed), the  $\tau$ -polarisation results for  $\mathcal{A}_e$  and  $\mathcal{A}_\tau$ , the SLD measurement of  $\mathcal{A}_e$  and the 6 parameter heavy flavour results.

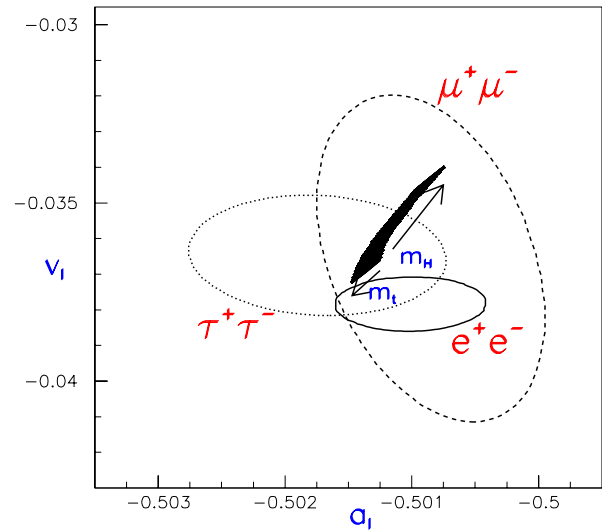
The main information content in these measurements is from  $R_b^0 = \Gamma_b/\Gamma_{\text{had}}$  (which, using  $\Gamma_{\text{had}}$  from the lineshape, gives  $v_b^2 + a_b^2$ ),  $R_c^0 (v_c^2 + a_c^2)$ ,  $A_e$  from LEP/SLD ( $v_e/a_e$ ),  $A_{\text{FB}}^{0,b}$  ( $v_b/a_b$ ,  $v_e/a_e$ ),  $\mathcal{A}_b$  ( $v_b/a_b$ ),  $A_{\text{FB}}^{0,c}$  ( $v_c/a_c$ ,  $v_e/a_e$ ) and  $\mathcal{A}_c$  ( $v_c/a_c$ ). The constraint  $\alpha_s(M_Z) = 0.119 \pm 0.003$  is imposed (although the results are rather insensitive to this as discussed below).

If lepton universality is not assumed then information on the lepton couplings comes from the direct measurements of  $\mathcal{A}_e$  and  $\mathcal{A}_\tau$ , as well as from the lepton forward-backward asymmetries and lepton partial widths and also from the heavy quark forward-backward asymmetries. These are contained in the 9 parameter lineshape results and the 6 parameter heavy flavour results respectively. Through correlations the other parameters also enter in these fits. The overall  $\chi^2$  of the fit is 2.3 for 5 df, giving a probability of 81%. If lepton universality is assumed then the  $\chi^2$  of the fit becomes 5.7 for 4 df, giving a probability of 22%.

### 4.1 Lepton couplings

*Lepton universality* is a hypothesis of the SM and it is clearly important to test it as precisely as possible. The results of the fit for the individual lepton couplings are shown in Fig. 1, together with the 70% confidence level contours. The signs are plotted taking  $a_e < 0$ . Using this convention (this is justified from  $\nu$ -electron scattering results [16]), the signs of all couplings are uniquely determined from LEP data alone. The data are compatible with the hypothesis of *lepton universality* and with the SM expectations. The results test this hypothesis at the level of 0.1% for  $a_\ell$ , but only at the 5-10% level for  $v_\ell$ .

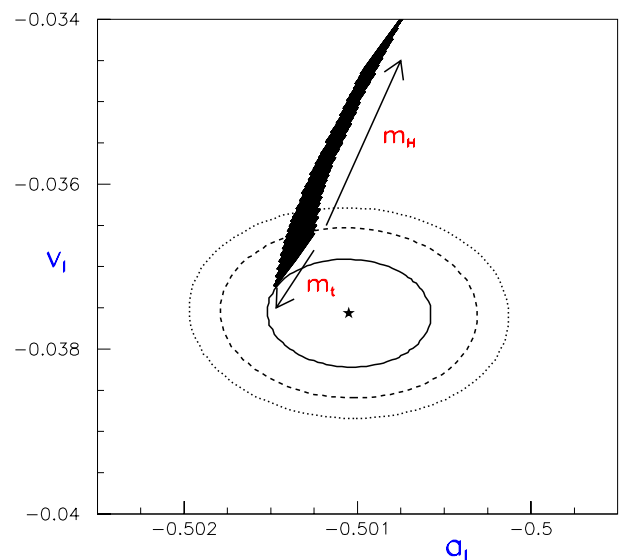
If the hypothesis is assumed then the computed couplings are given in Table 2 and shown in Fig. 2. The constraints from the individual measurements are shown in Fig. 3. It can be seen that  $a_\ell$  is essentially determined by  $\Gamma_l$ , whereas  $v_\ell$  is determined, in order of accuracy, by the measurements of  $A_{\text{LR}}$ , the  $\tau$ -polarisation and  $A_{\text{FB}}^{0,\ell}$ . In the context of the SM these measurements, in particular  $A_{\text{LR}}$ , favour a rather light Higgs boson mass.



**Fig. 1.** Contours of 70% probability in the  $v_\ell$ - $a_\ell$  plane from LEP and SLD measurements. The solid region corresponds to the Standard Model prediction for  $168.8 \leq m_t$  [GeV]  $\leq 178.8$  GeV and  $90 \leq m_H$  [GeV]  $\leq 1000$  GeV. The arrows point in the direction of increasing values of  $m_t$  and  $m_H$

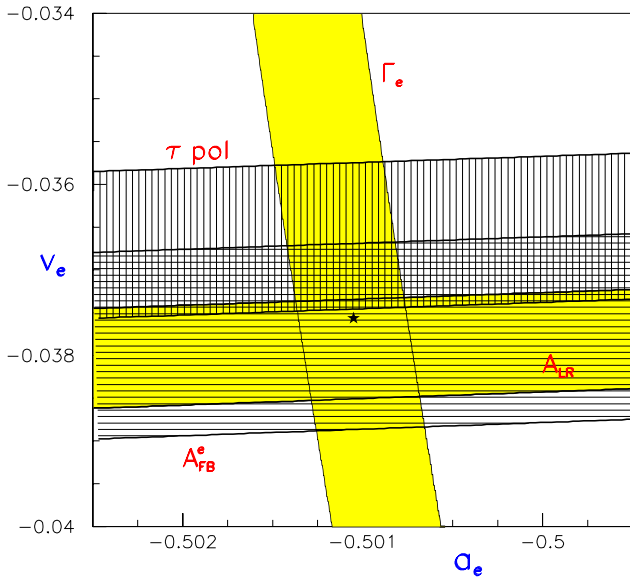
**Table 2.** Lepton vector and axial-vector couplings assuming lepton universality

	LEP	LEP+SLD
$v_\ell$	$-0.03719 \pm 0.00061$	$-0.03756 \pm 0.00042$
$a_\ell$	$-0.50107 \pm 0.00030$	$-0.50105 \pm 0.00030$
$v_\nu$	$+0.50127 \pm 0.00095$	$+0.50128 \pm 0.00095$

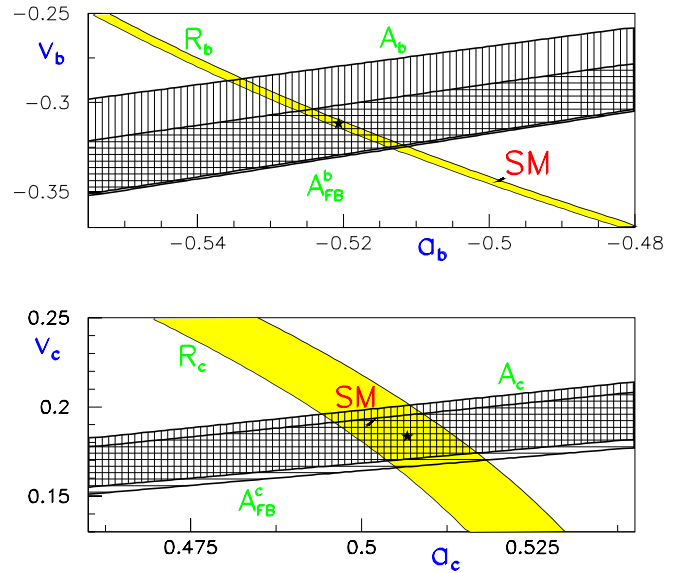


**Fig. 2.** Contours of 70%, 97% and 99% probability in the  $v_\ell$ - $a_\ell$  plane from LEP and SLD measurements. The solid region corresponds to the Standard Model prediction for  $168.8 \leq m_t$  [GeV]  $\leq 178.8$  GeV and  $90 \leq m_H$  [GeV]  $\leq 1000$  GeV. The arrows point in the direction of increasing values of  $m_t$  and  $m_H$

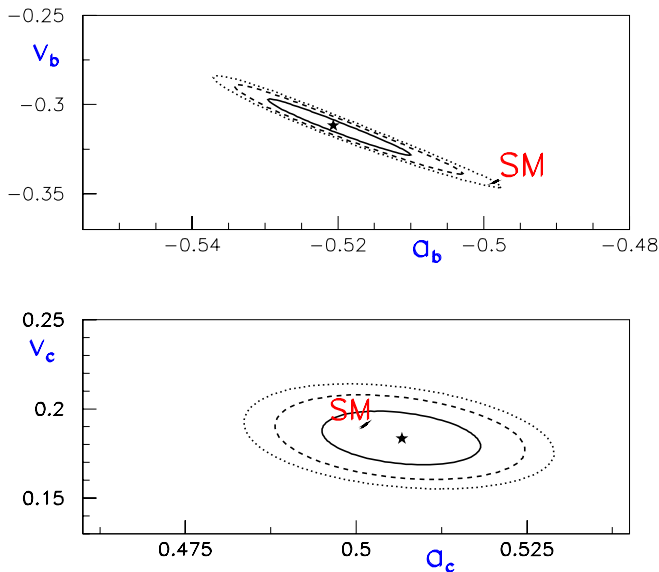
<sup>2</sup> See also [1], [4],[14] and [15].



**Fig. 3.** Constraints on  $v_\ell$  and  $a_\ell$  from individual measurements



**Fig. 5.** Constraints on the b and c-quark vector and axial-vector couplings, from individual measurements



**Fig. 4.** Results of a fit to the b and c-quark vector and axial-vector couplings. The contours are for the 70, 95 and 99% confidence limits

## 4.2 Heavy quark couplings

The results of the fit for  $v_b$  and  $a_b$  are given in Table 3 and Fig. 4. Also shown are the SM predictions corresponding to  $m_t = 173.8 \pm 5.0$  GeV and  $90 \leq m_H$  [GeV]  $\leq 1000$ . The corresponding results for  $v_c$  and  $a_c$  are also shown. Note that there is a very strong anti-correlation between  $v_b$  and  $a_b$ . The constraints from the individual measurements are shown in Fig. 5.

The b(or c)-quark couplings can also be expressed in terms of the left-handed  $l_b = (v_b + a_b)/2$  and right-handed  $r_b = (v_b - a_b)/2$  couplings. The results are shown in Fig. 6. It can be seen that, whereas the c-quark couplings are reasonably compatible with the SM, those for

**Table 3.** Results, plus correlation matrix, of a fit to the vector and axial-vector couplings of b and c quarks

parameter	fitted value	$v_b$	$a_b$	$v_c$	$a_c$
$v_b$	$-0.3118 \pm 0.0101$	1.00	-0.98	-0.15	0.04
$a_b$	$-0.5206 \pm 0.0063$		1.00	0.15	-0.01
$v_c$	$0.183 \pm 0.010$			1.00	-0.29
$a_c$	$0.5067 \pm 0.0075$				1.00

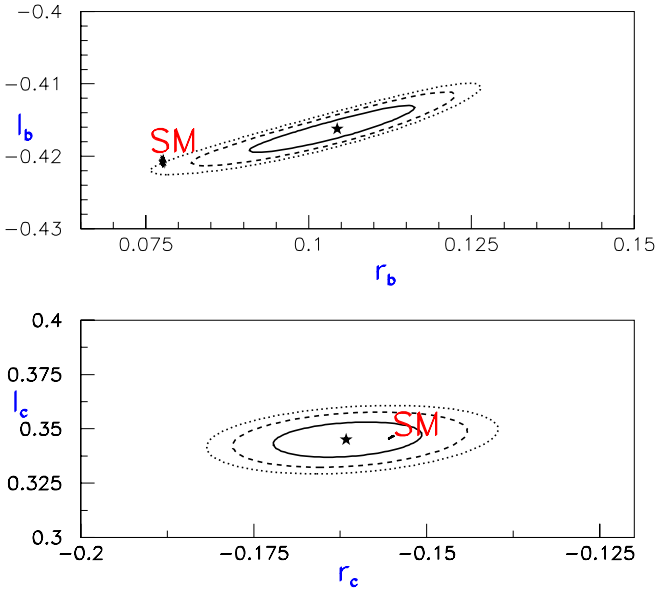
the b-quark, in particular the right-handed coupling, are in poor agreement with the SM expectations. The fitted values of  $v_b$  and  $a_b$  (or  $l_b$  and  $r_b$ ) give a value of  $R_b^0$  greater than the SM value, and a value of  $\mathcal{A}_b$  (or  $A_{FB}^{0,b}$ ) less than the SM value. In that sense the b-quark data are mutually consistent with the observed deviations from the SM.

## 4.3 Discussion of results

The results for the Z-lepton couplings from the different methods are compatible both with each other<sup>3</sup> and with the SM, provided the Higgs Boson is relatively light. The c-quark couplings are also compatible with the SM. However, as can be seen from Fig. 4, the b-quark couplings appear to be only marginally compatible with the SM. The point in the SM band which is closest to the fitted data values corresponds to  $m_t = 168.8$  GeV and  $m_H = 90$  GeV. The  $\chi^2$  probability for compatibility to this point is 1.3%.

It is worthwhile therefore exploring further this possible discrepancy. In the fits the assumed value of  $\alpha_s(M_Z)$  was taken to be  $0.119 \pm 0.003$ . If a central value of 0.116

<sup>3</sup> The results now are more consistent than in previous years; see e.g. [1],[4].



**Fig. 6.** Results of a fit to the b and c-quark left and right-handed couplings. The contours are for the 70, 95 and 99% confidence limits

is used then the leptonic couplings are unchanged and the shifts in the b- and c-quark couplings are 0.0003 or less. Hence the results are not very sensitive to  $\alpha_s(M_Z)$ . This is to be expected since the ratios  $R_b^0$  and  $R_c^0$  are, by construction, rather insensitive to  $\alpha_s(M_Z)$ .

The results from the SLD Collaboration on  $A_{LR}$ ,  $A_b$  and  $A_c$  [9, 10] require a precise determination of the degree of polarisation of the electron beam. It can be noted that the values of  $A_e$  (from  $A_{LR}$ ),  $A_b$  (from  $\tilde{A}_{FB}^b$ ) are above and below the SM predictions respectively. Since, in both cases, what is measured is proportional to the product of the polarisation and the required parameter, the measurements cannot both be reconciled with the SM simply by a change in the value of the electron polarisation. It is worth stressing that the uncertainty on  $A_{LR}$  due to the polarisation is between 0.7% and 1.1% for the published and preliminary data sets. This is to be compared to the overall statistical component of the error which is about 1.5%.

The results for  $A_{FB}^{0,b}$  measure the product of  $A_e$  and  $A_b$ . Thus the value of  $A_{FB}^{b\bar{b}}$  extracted depends critically on that of  $A_e$ . In the standard fits above the information on  $A_e$  comes from all of the data and the fitted value is  $A_e = 0.1491 \pm 0.0017$ . Most of the information comes from the measurements of  $A_{LR}$ , the  $\tau$ -polarisation and  $A_{FB}^{0,\ell}$ . In the SM the value of  $A_e$  increases for increasing  $m_t$  and decreasing  $m_H$ . However, as  $m_t$  is now well constrained, the main variation is from  $m_H$ . As can be seen from Fig. 2, the lepton coupling data favour a light Higgs. Within the ranges  $168.8 \leq m_t$  [GeV]  $\leq 178.8$  and  $90 \leq m_H$  [GeV]  $\leq 1000$  the closest SM value is 0.1477, which corresponds to  $m_t = 178.8$  GeV and  $m_H = 90$  GeV. The value of  $A_e$  which corresponds to the 95% upper limit on  $m_H$  (namely about 300 GeV) is 0.1460. The values of  $v_b$  and  $a_b$  extracted when these two values for  $A_e$  are im-

posed for the measurement of  $A_{FB}^{0,b}$  are given in Table 4. Also given are the  $\chi^2$  probabilities that the result is compatible with the closest SM value. It can be seen that the  $\chi^2$  probability increases as  $A_e$  increases to about 5% for  $A_e = 0.1460$ . If  $A_{FB}^{0,b}$  is removed from the fit then the probability increases to 6.6%.

Although the c-quark couplings are reasonably compatible with the SM it can be noted that, as for b-quarks, the measured values of  $A_{FB}^{0,c}$  and  $A_c$  are both below the SM predictions. However, the errors for c-quarks are currently larger than for b-quarks, so the differences are less significant.

## 5 Electroweak fits for the Higgs boson mass

The precision data discussed above, together with additional data, are sufficiently accurate to constrain the mass of the Higgs boson in electroweak fits. The additional measurements used are  $M_W = 80.390 \pm 0.064$  GeV,  $\sin^2\theta_W = 0.2254 \pm 0.0021$  from deep inelastic neutrino-nucleon experiments and  $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.2321 \pm 0.0010$  from the flavour averaged forward-backward asymmetry in Z hadronic events  $\langle Q_{FB} \rangle$  [11]. The value of  $M_W$  is the current average of the Fermilab and CERN values. The value of  $\sin^2\theta_W$  is from the NuTeV [17] and CCFR [18] experiments, and the dependence of the result on  $m_t$  and  $m_H$  [17] is taken into account. The top quark mass [2]  $m_t = 173.8 \pm 5.0$  GeV is used as a constraint in the fits.

The parameters used in these fits are  $M_Z$ ,  $m_t$ ,  $\alpha_s(M_Z)$  and  $\alpha(M_Z)$  as well as the Higgs mass  $m_H$ . An external constraint  $1/\alpha^5(M_Z) = 128.878 \pm 0.090$  [19] is used in the fits discussed below. Note that this value is for 5 quark flavours only with the effects of the top quark adjusted to the fitted top quark mass.

The results of the fits to all electroweak data give a central value for  $m_H$  of 77 GeV, and a one-sided 95% c.l. upper limit of 246 GeV; see Table 5.<sup>4</sup> The lower limit from direct searches of about 90 GeV [20] is not used in the limits here. The upper limit does not take into account the theoretical uncertainty due to missing higher order terms. Including an estimate of these (as discussed in [11]) increases this limit to 262 GeV; that is, an increase of about 16 GeV. It is of great importance, particularly in the consideration of the construction of new accelerators, to understand if these values are reliable. One can adopt (at least) two approaches to these fits:

- 1) The overall  $\chi^2$  of 14/13 d.f. (prob. = 35%) for the fit to all data is reasonably good. The distribution of the pulls<sup>5</sup> has a mean value of  $-0.1 \pm 0.2$  and an rms of 0.9, and so is compatible with the expected Gaussian distribution. The two measurements with the largest  $\chi^2$ 's ( $A_{FB}^{0,b}$  and  $A_{LR}$ ) are just the expected ‘‘tails’’ of the distribution. However, these are the two most sensitive measurements to  $m_H$ .

<sup>4</sup> The fits have been made using ZFITTER version 5.12 [21].

<sup>5</sup> The pull is defined as the difference between the measured and fitted values, divided by the error on the quantity.

**Table 4.** Values of  $v_b$  and  $a_b$  for different assumptions about the use of  $A_{\text{FB}}^{0,b}$ . The SM values used correspond to  $m_t = 168.8$  GeV and  $m_H = 90$  GeV

conditions on $A_{\text{FB}}^{0,b}$	$v_b$	$a_b$	$\chi^2$ prob. for SM
none	$-0.3118 \pm 0.0101$	$-0.5206 \pm 0.0063$	1.3%
$A_e = 0.1477$	$-0.3154 \pm 0.0094$	$-0.5185 \pm 0.0059$	1.7%
$A_e = 0.1460$	$-0.3199 \pm 0.0097$	$-0.5157 \pm 0.0062$	4.8%
remove	$-0.3147 \pm 0.0119$	$-0.5189 \pm 0.0075$	6.6%

**Table 5.** Results of electroweak fits to  $m_t$  and  $m_H$  for different sets of data. The fourth column gives the 95% one-sided confidence level upper limit on  $m_H$ . This upper limit does not include the uncertainty in the theory. A fitted value of  $\alpha_s(M_Z) = 0.119 \pm 0.003$  is also obtained in these fits

data used	$m_t$ GeV	$m_H$ GeV	95% limit on $m_H$ GeV	$\chi^2$ prob. of fit
all data	$171.1^{+4.9}_{-4.8}$	$77^{+85}_{-47}$	246	35%
without $A_{\text{LR}}$	$172.5^{+4.9}_{-4.8}$	$150^{+133}_{-79}$	410	63%
without $A_{\text{FB}}^{0,b}$	$169.7^{+4.8}_{-4.2}$	$36^{+66}_{-22}$	172	56%
without $A_{\text{LR}}$ and $A_{\text{FB}}^{0,b}$	$171.7^{+5.0}_{-4.9}$	$105^{+124}_{-70}$	348	65%
scale $A_{\text{LR}}$ and $A_{\text{FB}}^{0,b}$	$171.5^{+4.9}_{-4.9}$	$92^{+106}_{-61}$	303	70%

2) The quantities which are most sensitive to  $m_H$  are, in order of current sensitivity,  $A_{\text{LR}}$ ,  $A_{\text{FB}}^{0,b}$ ,  $\Gamma_Z$ ,  $P_\tau$ ,  $M_W$  and  $A_{\text{FB}}^{0,\ell}$ . These 6 quantities contribute 7.5 to the  $\chi^2$ . The individual values of the pulls for these 6 quantities are -1.7, -1.8, -0.8, -0.4, 0.3 and 0.7 respectively. The central value for  $m_H$  is sensitive to which data are included. For example, if a fit is performed without the inclusion of  $A_{\text{LR}}$ , the most sensitive quantity to  $m_H$ , then, as shown in Table 5, the one-sided 95% c.l. upper limit increases to 410 GeV, plus the theory error. However if  $A_{\text{FB}}^{0,b}$  (alone) is excluded from the fit, then the 95% c.l. upper limit on  $m_H$  becomes 172 GeV. If both  $A_{\text{LR}}$  and  $A_{\text{FB}}^{0,b}$  are excluded, then the 95% c.l. upper limit on  $m_H$  becomes 348 GeV. Although the 6 most sensitive quantities to  $m_H$  have a reasonable total contribution to  $\chi^2$ , the two most sensitive quantities,  $A_{\text{LR}}$  and  $A_{\text{FB}}^{0,b}$  have a  $\chi^2$  contribution of 6.0. If the errors on these two quantities are scaled according to the Particle Data Book recipe, then the 95% c.l. upper limit on  $m_H$  becomes 303 GeV.

Of particular interest is the extent to which the data indicate that the Higgs is light. As can be seen from the fits above, the quantity most responsible for driving the limit higher is  $A_{\text{FB}}^{0,b}$ . However, there is no good reason to reject either the  $A_{\text{FB}}^{0,b}$  or  $A_{\text{LR}}$  measurements at the present time. The value of  $A_b$ , which contributes to the b-quark couplings not being very compatible with the SM, has little influence on these fits; apart from increasing the  $\chi^2$ . For example, if the value of  $A_b$  is set to the SM value instead of the experimentally measured value, then the Higgs mass changes by less than 1 GeV.

In summary, the best estimate is that the Higgs is relatively light. However, the data are not fully compatible, so some caution in interpreting the data is necessary.

## 6 Summary and conclusions

The vector and axial-vector couplings of both the leptons and heavy quarks have been extracted from the most recent electroweak data. The lepton couplings support the hypothesis of *lepton universality*.

The c-quark couplings are compatible with SM expectations. However, those of the b-quark agree with the SM at only the 1% level. The main discrepancy is for the right-handed coupling of the b-quark. If real, this would not be easily interpreted in terms of the usual extensions to the SM. However, it should be noted that the data used are mostly still preliminary and that the completed final analyses of all the LEP data are eagerly awaited. Possible future running of the SLC would clearly be of great benefit in resolving these questions.

Although the present results on the b-quark couplings are clearly interesting, they do not as yet provide compelling evidence for physics beyond the SM.

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**Note added in proof.** Updated measurements of some heavy flavour results were presented at the 34th Rencontres de Moriond, March 1999. The most significant update is to  $A_b = 0.908 \pm 0.027$ , which comes mainly from the SLD measurement, reported by N. de Groot. This updated value is somewhat closer to the SM value. Including all the updated heavy flavour results in the fit changes the compatibility of the b-quark couplings with the SM from a value of 1.3%, as given in this paper, to 3.6%. The conclusions remain unaltered.