ELECTROWEAK FITS AND CONSTRAINTS ON THE HIGGS MASS

PETER B. RENTON
Denys Wilkinson Building, University of Oxford, Oxford OX1 3RH, UK
E-mail: p.renton1@physics.ox.ac.uk

The current status of the quantities entering into the global electroweak fits is reviewed, highlighting changes since Summer 2003. These data include the precision electroweak properties of the Z and W bosons, the top-quark mass and the value of the electromagnetic coupling constant $\alpha(M_Z)$, at a scale M_Z. Using these Z and W (high Q^2) data, the value of the Higss mass is extracted, within the context of the Standard Model (SM). The consistency of the data, and the overall agreement with the SM, are discussed.

1 The precision electroweak data

This report contains an update on the values of the precision electroweak properties and fits within the context of the SM, with respect to [1], where more details can be found. The e^+e^- data are from the ALEPH, DELPHI, L3 and OPAL experiments at LEP, from both the LEP1 and LEP2 phases, and also from the SLD experiment at SLAC. The $p\bar{p}$ data come from the CDF and D0 experiments from both Run 1 ($\sqrt{s}$=1.8 TeV) and Run 2 ($\sqrt{s}$=1.96 TeV).

1.1 Z boson

The coupling of the Z boson to $f\bar{f}$ is specified by the vector ($g_{\rm Vf}$) and axial-vector ($g_{\rm Af}$) couplings. These can be expressed in terms of ρ and the effective weak mixing angle $\sin^2\theta^{\rm f}_{\rm eff}$ by

$$g_{\rm Af} = \sqrt{\rho}T_3^f, g_{\rm Vf}/g_{\rm Af} = 1 - 4 \mid q_f \mid \sin^2\theta^{\rm f}_{\rm eff} \quad (1)$$

where q_f is the charge, T_3^f is the third component of weak isospin. The Z partial width $\Gamma_f \propto g^2_{\rm Vf} + g^2_{\rm Af}$, and the pole forward-backward asymmetry, which has been measured for e, μ and τ pair final states, and also for c and b quarks, is

$$A^{0,f}_{FB} = \frac{3}{4}A_e A_f, \quad (2)$$

where

$$A_f = \frac{2g_{\rm Vf}/g_{\rm Af}}{1 + (g_{\rm Vf}/g_{\rm Af})^2}. \quad (3)$$

The lepton couplings can be extracted from the τ polarisation (giving A_e, A_τ), the SLAC polarised electron asymmetry $A_{\rm LR}$ (A_e) and the forward-backward asymmetries for leptons (A_ℓ, ℓ=e,μ,τ). The results are unchanged with respect to [1] and are reasonably compatible with lepton universality, with $g_{\rm Al}/g_{\rm Ae}$ = 1.0002 $\pm$ 0.0014 and 1.0019 $\pm$ 0.0015, for l=μ,τ respectively. The uncertainties are larger for the vector-couplings, with $g_{\rm V\mu}/g_{\rm Ve} = 0.962 \pm 0.063$ and $g_{\rm V\tau}/g_{\rm Ve} = 0.958 \pm 0.029$. Assuming lepton universality, these asymmetries give a value of $A_{\rm e}$ = 0.1501 $\pm$ 0.0016. Within the context of the SM this favours a light Higgs mass. The invisible width of the Z boson allows the number of light neutrinos to be extracted (assuming Γ_ν/Γ_l from the SM), and gives N_ν = 2.9841 $\pm$ 0.0083, which is 1.9 σ below 3.

In the heavy-quark sector there are updates in the results from SLD. All the LEP and SLD results are now final, but the combination is not yet finalised. The quantities measured are $R_{\rm b} = \Gamma_{\rm b}/\Gamma_{\rm had}$, $R_{\rm c} = \Gamma_{\rm c}/\Gamma_{\rm had}$, $A^{0,\rm b}_{\rm FB}$, $A^{0,\rm c}_{\rm FB}$, $A_{\rm b}$ and $A_{\rm c}$ (which are obtained from the left-right-forward-backward asymmetries). There are additional (since Summer 2003) theoretical uncertainties, arising from the extrapolation of off-peak measurements to the peak, of 0.0002 and 0.0005 added to $A^{0,\rm c}_{\rm FB}$ and $A^{0,\rm b}_{\rm FB}$ respectively (see [2] for more details). There is good internal consistency in the determinations of $R_{\rm b}$, $R_{\rm c}$, $A^{0,\rm b}_{\rm FB}$ and $A^{0,\rm c}_{\rm FB}$. The combined LEP and SLD re-

Table 1. Combination of Z heavy flavour results

quantity	value	error
$R_{\rm b}$	0.21630	0.00066
$R_{\rm c}$	0.1723	0.0031
$A_{\rm FB}^{0,\,\rm b}$	0.0998	0.0017
$A_{\rm FB}^{0,\,\rm c}$	0.0706	0.0035
$\rm A_b$	0.923	0.020
$\rm A_c$	0.670	0.027

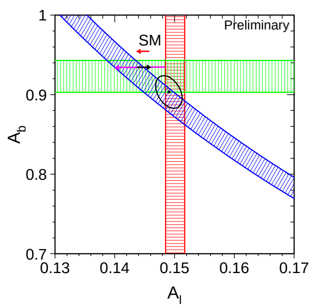

Figure 1. The couplings $\rm A_b$ and $\rm A_e$, both from direct measurements and from $A_{\rm FB}^{0,\,\rm b}$.

sults are given in Table 1. The largest correlation is -0.18, between $R_{\rm b}$ and $R_{\rm c}$. The χ^2/df for the combination is 53/(105-14), giving a probability close to 100%. If statistical errors only are used in the combination then this becomes 92/(105-14), indicating that the systematic errors appear to be overestimated.

The direct determinations of $\rm A_e$ and $\rm A_b$ are shown in figure 1. Also shown is the band in the $\rm A_e$ $\rm A_b$ plane, traced out by $A_{\rm FB}^{0,\,\rm b}$. The combined value, and the 68% cl, are also shown, as is the SM prediction. It can be seen that the joint result from these data is in poor agreement with the SM. The value of $A_{\rm FB}^{0,\,\rm b}$ favours a rather heavy Higgs mass.

Figure 2 shows the determinations of $\sin^2\theta_{\rm eff}^{\rm lept}$. The overall χ^2 probability is reasonable (8.4%), but the value obtained from purely leptonic processes ($\sin^2\theta_{\rm eff}^{\rm lept}$=0.23113

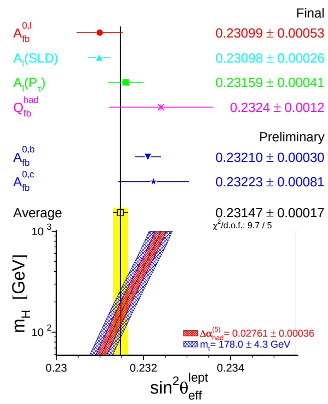

Figure 2. Determinations of $\sin^2\theta_{\rm eff}^{\rm lept}$.

$\pm$ 0.00021) is some 2.8σ different to that obtained using heavy quarks ($\sin^2\theta_{\rm eff}^{\rm lept}$=0.23213 $\pm$ 0.00029). This comes mostly from the 2.8σ difference in the SLD $A_{\rm LR}$ and $A_{\rm FB}^{0,\,\rm b}$ values.

1.2 W boson

The W boson is produced singly at the Tevatron (eg $u + \bar{d} \rightarrow W^+$). The leptonic decays W$\rightarrow$ $\ell\nu$ (with $\ell = e, \mu$) are used to determine the W mass and width, using the transverse mass or $\rm p_T^\ell$. From Run 1 the values $M_{\rm W}$ = 80.433 $\pm$ 0.079 GeV (CDF) and 80.483 $\pm$ 0.084 GeV (D0) were obtained. Taking into account common systematics, the combined Run 1 values are $M_{\rm W}$ = 80.452 $\pm$ 0.059 GeV and $\Gamma_{\rm W}$ = 2.102 $\pm$ 0.106 GeV [3]. Run 2 analyses are currently underway.

At LEP2 the W bosons are pair-produced in $\rm e^+e^- \rightarrow W^+W^-$. The analyses are still in progress. The statistical uncertainties from the $\ell\nu q\bar{q}^{'}$ and $q\bar{q}^{'}q\bar{q}^{'}$ channels are similar. However, there is at present a large systematic uncertainty (97 MeV) in the $q\bar{q}^{'}q\bar{q}^{'}$ channel, due to final-state interaction effects. This is mostly from colour reconnection, with a smaller contribution from Bose Einstein correlations. This means that the $q\bar{q}^{'}q\bar{q}^{'}$ channel carries only 10% of the weight in the LEP2 average. The preliminary LEP2 values are $M_{\rm W}$ = 80.412 $\pm$ 0.042 GeV and $\Gamma_{\rm W}$ = 2.152

± 0.091 GeV.

The combined Tevatron and LEP2 values are $M_{\rm W} = 80.425 \pm 0.034$ GeV and $\Gamma_{\rm W} = 2.133 \pm 0.069$ GeV. $\Gamma_{\rm W}$ is compatible with the SM value of 2.097 ± 0.003 GeV. The world average $M_{\rm W}$ value favours a low Higgs mass in the context of the SM.

2 The SM parameters

The SM parameters are taken to be $M_{\rm Z}$, G_F, $\alpha(M_{\rm Z})$ and $\alpha_{\rm s}(M_{\rm Z})$ (the electromagnetic and strong coupling constants at the scale $M_{\rm Z}$), and the top-quark mass $m_{\rm t}$. Through loop diagrams measurements of the precision electroweak quantities are sensitive to $m_{\rm t}$ and, the 'unknown' in the SM, $m_{\rm H}$. The SM computations use the programs TOPAZ0 and ZFITTER. The latter program (version 6.40) incorporates the recent fermion 2-loop corrections to $\sin^2\theta_{\rm eff}^{\rm lept}$ and full 2-loop, and leading 3-loop, corrections to $M_{\rm W}$ [4].

2.1 top-quark mass

The D0 Collaboration have recently improved their Run 1 measurement using a weighting method based on the matrix element, giving $m_{\rm t} = 179.0 \pm 3.5$ (stat) $\pm$ 3.8 (syst) GeV. The CDF Run 1 value is $m_{\rm t} = 176.1 \pm 4.2$ (stat) $\pm$ 5.1 (syst) GeV. Taking into account common systematic uncertainties the combined value is [5] $m_{\rm t} = 178.0 \pm 4.3$ GeV, with statistical and systematic error components of 2.7 and 3.3 GeV respectively. This is to be compared to the previous value of $m_{\rm t} = 174.3 \pm 5.1$ GeV.

Run 2 values have been obtained by both the CDF and D0 Collaborations, but these have not yet been included in the average.

2.2 $\alpha(M_{\rm Z})$

The value of α at the scale $M_{\rm Z}$ requires the use of data on $e^+e^- \to$hadrons at low energies and the use of perturbative QCD at higher energies. The various estimations of $\alpha(M_{\rm Z})$ differ in the extent to which QCD is used, as well as in the data used in the evaluation. The quantity needed is the hadronic contribution $\Delta\alpha^{(5)}_{\rm had}$ and the value used by the LEP EWWG [1] is $\Delta\alpha^{(5)}_{\rm had}(M_{\rm Z}) = 0.02761 \pm 0.00036$. Recent data from the CMD-2 and KLOE Collaborations has been consider in [6], and the authors conclude that the value just quoted is still valid.

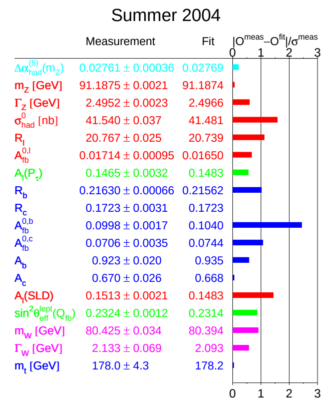

Figure 3. Measured and SM fitted values of electroweak quantities.

3 Electroweak fits

The measurements used in the global SM electroweak fits, and the fitted values, are shown in figure 3. The SM fit to these high Q^2 data gives

$$m_t = 178.2 \pm 3.9 \text{ GeV}$$
$$m_H = 114 \,^{+69}_{-45} \text{ GeV}$$
$$\alpha_s(M_{\rm Z}) = 0.1186 \pm 0.0027.$$

The χ^2/df is 15.8/13, giving a probability of 26%. The variation of the fit χ^2, compared to the minimum value, is shown in the 'blue-band' plot of figure 4, as a function of $m_{\rm H}$. Also shown is the direct search limit of 114 GeV. The one-sided 95% upper limit is $m_{\rm H} \leq 260$ GeV. This includes the theoretical uncertainty (blue-band) which is evaluated by considering the uncertainties in the

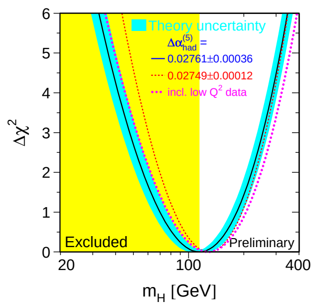

Figure 4. Variation of χ^2 versus $m_{\rm H}$.

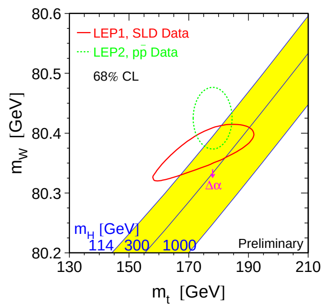

Figure 5. Direct versus indirect $m_{\rm t}$ and $M_{\rm W}$ measurements.

new 2-loop calculations [4]. If the more theory driven value $\Delta\alpha^{(5)}_{\rm had}(M_{\rm Z}) = 0.02749 \pm 0.00012$ is used, then $m_{\rm H}$ increases to 129 GeV.

Since 2003 the main changes have been the change in $m_{\rm t}$ ($\delta m_{\rm H} \simeq +20$ GeV) and the new 2-loop effects ($\delta m_{\rm H} \simeq +6$ GeV).

The direct versus indirect values of $m_{\rm t}$ and $M_{\rm W}$ is a powerful test of the SM; see figure 5. The contours shown are for the 68% cl. It can be seen that there is a reasonable degree of overlap and that the data prefer a light Higgs mass.

The above fits use only high Q^2 data. There are also low Q^2 data[7] from Atomic Parity Violation in ^{133}Cs (Q_W = -72.74 $\pm$ 0.46), the SLAC polarised electron Moller scattering experiment E158 ($\sin^2\theta^{\rm lept}_{\rm eff} = 0.2333 \pm 0.0016$) and the deep-inelastic $\nu(\bar{\nu})$ experiment NuTeV ($\sin^2\theta_{\rm W} = 0.2277 \pm 0.0016$). The NuTeV value can be used to extract $M_{\rm W}$, and gives a value 3.1σ below that from direct measurement. Including all these low Q^2 data in the SM fit increases $m_{\rm H}$ by 14 GeV to 128 GeV, and the χ^2 probability drops to 5.4%, essentially due to the NuTeV result.

4 Conclusions

There has been steady progress on both the experimental and theoretical fronts. There are still issues with $A^{0,\rm b}_{\rm FB}$ and NuTeV (both $\simeq 3\sigma$ effects). It is difficult to see how $A^{0,\rm b}_{\rm FB}$ can be resolved in the near future, but for NuTeV, the further evaluation of QED and QCD effects, together with the NOMAD results, should help.

The SM fits favour a light Higgs mass, $m_{\rm H} = 114\,^{+69}_{-45}$ GeV, and a 95% cl upper limit of 260 GeV. Thus the Higgs boson appears to be relatively light. Improved measurements of both $m_{\rm t}$ and $M_{\rm W}$ at the Tevatron, and then the LHC, will significantly improve the precision of the indirect estimation of $m_{\rm H}$.

Acknowledgments

I wish to thank the LEP EWWG, in particular Martin Grünewald, for their help.

References

1. The LEP Collaborations and EWWG; CERN-EP/2003-091 and hep-ex/0312023 (2003).
2. R. Hawkings, these proceedings.
3. Combination of CDF and D0 results on W boson mass and width, hep-ex/0311039 (2003).
4. M. Awramik et al., hep-ph/0311148, 0407317; M. Faisst et al. Nucl. Phys B665 (2003) 649.
5. Combination of CDF and D0 results on the top-quark mass, hep-ex/0404010 (2004).
6. B. Pietrzyk and H. Burkhardt, LAPP-EXP 2004-4, (2004).
7. P. Langacker, these proceedings