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Global fit to electroweak precision data

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Abstract. Electroweak precision measurements performed at LEP, SLC and at the Tevatron are sensitive to higher order corrections within the Standard Model of particle physics and can be used to test the consistency of the theory at the quantum level. The present status is reviewed here.

1 Introduction

The experiments at LEP, SLC and the Tevatron have provided a wealth of precision measurements which test the Standard Model at quantum level. These precision observables, since not directly experimental observables sometimes named "pseudo-observables", depend on the Standard Model parameters $\alpha_{em}(m_Z)$, m_Z, α_s, m_t and on the Higgs mass m_H (and on the Fermi constant, G_F, and on all fermion masses). The precision observables determine basically four different types of radiative corrections, the effective ρ-parameter, $\rho_{eff}^{\mathrm{lept}}$ (from the leptonic width of the Z), the effective weak mixing angle , $\sin^2\theta_{eff}^{\mathrm{lept}}$ (all asymmetry-type measurements), special top-mass dependent corrections to the width of the b-quark, or corrections to the mass of the W boson. At this level, the data are precise enough to perform meaningful consistency checks among the results.

In total, there are over 100 different measurements, performed by the experiments during different data taking periods and with different methods, which are combined into a set of 20 precision measurements by the LEP electroweak working group [1]. The set of input data considered is presented in Table 1. Not all results are final, and not in all cases the averaging procedure has been published. The second-last column of the table shows the sensitivity to m_H of each observable, defined as $\left|\frac{\mathrm{d}\mathcal{O}}{\mathrm{d}\log(\mathrm{m_H})}/\sigma_{\mathcal{O}}\right|$; the last column gives the "pull", the difference between the measured and the best-fit value normalised to the error. The pull is determined w.r.t. a fit of the Standard Model to all data, as described in Sect. 3.

The largest pull, or contribution to the overall χ^2 of the fit, arises from the measurement of Z-couplings from neutrino-nucleon scattering, for historical reasons quoted as a measurement of the on-shell weak mixing angle, $\sin^2\theta_W(\nu N)$, which, however, has a relatively low sensitivity. Two other significant contributions to χ^2 arise from measurements of $\sin^2\theta_{eff}^{\mathrm{lept}}$ from the b-quark forward-backward asymmetry at LEP and from the left-right polarisation asymmetry at the SLC. In total, the value of χ^2 of the fit is 25.4 for 15 degrees of freedom, corresponding to a χ^2-probability of only 4.5 %. Before going into the detailed discussion of the fit results, some light needs to be shed on this low value of χ^2.

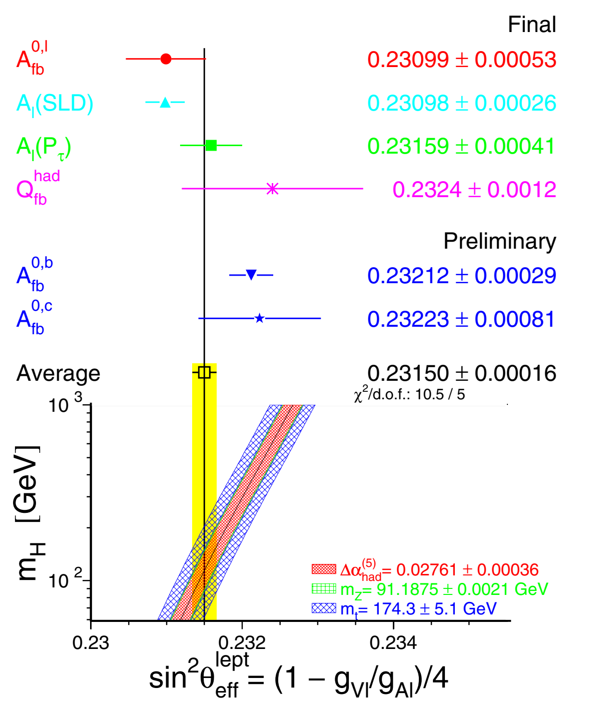

Fig. 1. Measurements of the effective electroweak mixing angle and their average

2 Consistency checks

All asymmetry-type measurements depend on the effective weak mixing angle for leptons, given by $\sin^2\theta_{eff}^{\mathrm{lept}} \equiv$

Table 1. Overwiew of electroweak precision observables

	Measurement	$m_{\rm H}$ sens.	Pull
LEP 1			
$m_{\rm Z}$ [GeV]	91.1875 ± 0.0021	–	+0.2
$\Gamma_{\rm Z}$ [GeV]	2.4952 ± 0.0023	2.8	−0.4
$\sigma^o_{\rm h}$ [nb]	41.540 ± 0.037	0.1	+1.7
R_ℓ	20.767 ± 0.025	0.8	+1.0
$A_{\rm FB}^{0,\,\ell}$	0.01714 ± 0.00095	2.1	+0.8
$\mathcal{A}_\ell$ fr. τ pol. $(*p)$	0.1465 ± 0.0032	2.8	−0.4
b & c quarks: $(*P)$			
$R_{\rm b}$ (incl. SLD)	0.21638 ± 0.00066	0.1	+0.9
$R_{\rm c}$ (incl. SLD)	0.1720 ± 0.0030	0.0	−0.1
$A_{\rm FB}^{0,\,\rm b}$	0.0997 ± 0.0016	3.9	−2.4
$A_{\rm FB}^{0,\,\rm c}$	0.0706 ± 0.0035	1.4	−1.0
$\rm q\overline{q}$ charge asym.: $(*p)$			
$\sin^2\theta^{\rm lept}_{eff}$ ($\langle Q_{\rm FB}\rangle$)	0.2324 ± 0.0012	1.0	+0.8
SLD			
$\mathcal{A}_\ell$	0.1513 ± 0.0021	4.4	+1.7
$\mathcal{A}_{\rm b}$	0.925 ± 0.020	0.0	−0.5
$\mathcal{A}_{\rm c}$	0.670 ± 0.026	0.2	+0.1
LEP 2 and $\rm p\overline{p}$ colliders $(*P)$			
$m_{\rm W}$ [GeV]	80.426 ± 0.034	4.4	+1.2
$\Gamma_{\rm W}$ [GeV]	2.139 ± 0.069	0.2	+0.7
νN scattering			
$\sin^2\theta_{\rm W}(\nu{\rm N})$	0.2277 ± 0.0016	1.8	+2.9
atomic parity violation			
Q_w(Cs)	-72.84 ± 0.46	0.5	+0.1
$\rm p\overline{p}$ colliders			
$m_{\rm t}$ [GeV]	174.3 ± 5.1	–	+0.0
$\Delta\alpha^{(5)}_{\rm had}$ $^{(a)}$	0.02761 ± 0.00036	–	−0.2
$(*P)$ preliminary, contains unpublished results			
$(*p)$ preliminary, average unpublished			

$^{(a)}$ The electroweak libraries require as input the value of the hadronic vacuum polarisation for five flavours, $\Delta\alpha^{(5)}_{\rm had}$, corresponding to $\alpha(m_{\rm Z})^{-1} = 128.936 \pm 0.049$.

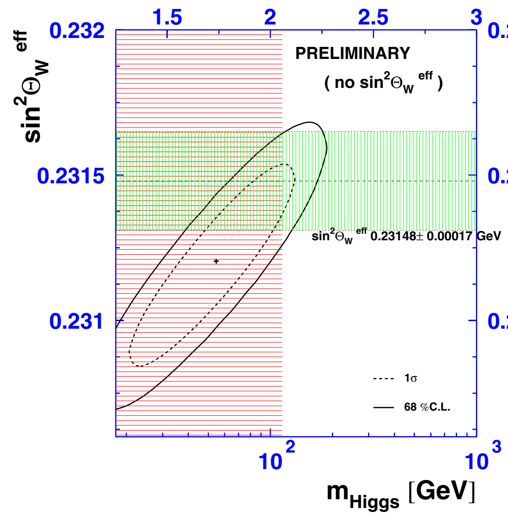

Fig. 2. Comparison of indirect determination of the effective weak mixing angle from electroweak measurements other than the asymmetry-type measurements of Fig. 1 with the average of the direct measurements in the $\sin^2\theta^{\rm lept}_{eff} - m_{\rm H}$ plane

$\frac{1}{4}(1 - \frac{g_l^v}{g_l^a})$. As is seen from Fig. 1 there is a noticeable discrepancy between the two most precise of such measurements, the average over the LEP experiments of the $\rm b\overline{b}$ forward-backward asymmetry and the SLD measurements of the left-right asymmetries. The overall χ^2-probability of the average over all measurements is still 6.2 %. It is worth mentioning here that the probability increases to 14 % if measurements for individual lepton species are used instead of the reduced input achieved by the assumption of lepton-universality. Leaving out the asymmetry-type measurements and performing a fit to the remaining data allows to determine the preferred value of $\sin^2\theta^{\rm lept}_{eff}$. Contour lines of such a fit are shown in Fig. 2; there is good agreement between this indirect determination and the average of all measurements of $\sin^2\theta^{\rm lept}_{eff}$, the numerical value being $\sin^2\theta^{\rm lept}_{eff\,{\rm ind}} = 0.23120 \pm 0.00038$.

No convincing model is known that might explain the $\mathcal{A}_\ell({\rm SLD}) - A_{\rm FB}^{0,\,\rm b}$ discrepancy. In the light of the above check, the individual measurements of $\sin^2\theta^{\rm lept}_{eff}$ might be replaced by the average in the fit; the resulting χ^2 then becomes 15 for 10 degrees of freedom, with a probability of 13 %; this still low probability is now completely due to the measurement of $\sin^2\theta_{\rm W}(\nu{\rm N})$ from neutrino-nucleon scattering.

A similar procedure applied to $m_{\rm W}$, *i.e.* using Z-pole data and $m_{\rm t}$ only to obtain a prediction of $m_{\rm W}$, results in $m_{\rm W\,ind} = 80.378 \pm 0.023$ GeV, with still acceptable agreement with the average of the direct measurements. The indirect value of $m_{\rm t}$ from the Z-pole data plus $m_{\rm W}$ is $m_{\rm t\,ind} = 179^{+11}_{-9}$ GeV, in perfect agreement with the direct measurement.

The largest single contribution to the high value of χ^2 in the electroweak fit stems from the discrepancy of $\sin^2\theta_{\rm W}(\nu{\rm N})$ from it's expectation value within the Standard Model. As may already be inferred from the relatively low sensitivity of this measurement, omitting it from the fit input does not significantly change the result – the Higgs mass turns out to be four GeV lower, but the χ^2-probability increases to 28 %. In this sense, the problem with $\sin^2\theta_{\rm W}(\nu{\rm N})$ factorises out from the electroweak fit. Nonetheless, all possible checks of this result should be made to see whether the origin is experimental, theoretical, just a fluctuation, or a first indication of new physics.

An electroweak fit without $\sin^2\theta_{\rm W}(\nu{\rm N})$ and using the average of the measurements of $\sin^2\theta^{\rm lept}_{eff}$ results in a χ^2-probability of 70 %. This shows that so-called "problems" of the electroweak fit are located in only three measurements, only two of which have a real impact on the fit result. To be able to continue and interpret the result, it is assumed in the next section that the discrepancy between $\mathcal{A}_\ell$(SLD) and $A_{FB}^{0,b}$ is due to a statistical fluctuation.

3 Discussion of fit results

The results of the Standard Model fit using ZFITTER [2] are shown in Table 2. Note that m_Z, m_t and $\Delta\alpha_{had}^{(5)}$ are Standard Model parameters constrained by precision input measurements. The result on α_s is given by the measurements of the hadronic Z width [1] by the LEP experiments and is quoted here without a theoretical QCD error, with sizes ranging between ∼0.0005 and ∼0.003 in the existing literature. The results on other parameters are not affected by these uncertainties, because large effects from α_s are only visible in the hadronic Z width, and without an external constraint on α_s, Γ_{had} does not contribute to the determination of electroweak parameters from the fit.

Table 2. Fit to all data with ZFITTER

χ^2 / DoF (prob.)	25.4/15 (χ^2 prob. = 4.5 %)
m_Z [GeV]	91.1875 ± 0.0021
m_t [GeV]	174.3 ± 4.5
$\Delta\alpha_{had}^{(5)}$	0.02767 ± 0.00035
α_s	**0.1186 ± 0.0027**
m_H [GeV]	$\mathbf{96^{+60}_{-38}}$
derived parameters	
$\sin^2\theta_W^{eff}$	0.23143 ± 0.00014
$\sin^2\theta_W$	0.22289 ± 0.00036
m_W	80.385 ± 0.019
largest correlations: $m_H - m_t$: 71 %	$m_H - \Delta\alpha_{had}^{(5)}$: 48 %

The Higgs mass with a value of $m_H = 96^{+60}_{-38}$ GeV is the main result of the fit. The global χ^2 as a function of m_H is shown in Fig. 3. The coloured area indicates the range in Higgs mass already excluded by direct searches at LEP 2, $m_H > 114.3$ GeV at 95 % CL. The shaded (blue) band indicates the maximum variation seen when modifying the Standard Model calculations [3] as implemented in the programs ZFITTER and TOPAZ0 [4]. The difference in m_H at the minimum of the two programs is only 2 GeV. The limiting curve on the low side is given by an inclusion of two-loop calculations on m_W [5], the limit on the high side comes from a special option in TOPAZ0.

When judging the stability of the result on m_H, it is important not to neglect the correlations among the fit

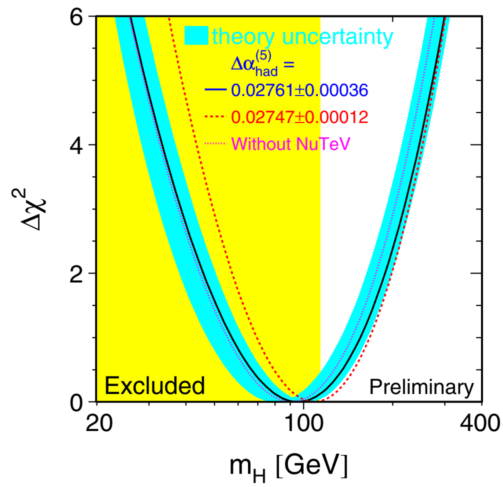

Fig. 3. Difference in global χ^2 w.r.t. the minimum for the Higgs mass. The *blue band* indicates theoretical systematic errors

results. The largest ones are given in the last line of Table 2. Spelt out clearly, these mean that a change in m_t by one standard deviation changes the Higgs mass by 71 % of its error, and a one-standard-deviation change of $\Delta\alpha_{had}^{(5)}$ changes m_H by about half of its error [2]. This strong effect on m_H distinguishes m_t and $\Delta\alpha_{had}^{(5)}$ from all other measurements, the reason being their relatively large uncertainties and their role as Standard Model input rather than being one of many measurements of loop effects.

The one-sided, 95 % CL upper limit on the value of the Higgs mass from the precision measurements only, not including the lower boundary from the direct searches into the exclusion limit, is the point where the $\Delta\chi^2$-curve reaches a value of 2.69. The limit thus obtained is $m_H <$ 219 GeV @ 95 % CL.

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[1] The set measurements of Z properties at LEP 1 given in the first four lines of Table 1 is equivalent to measurements of m_Z, Γ_{had}, $\Gamma_{\ell\ell}$ and Γ_{inv}.

[2] A new evaluation of radiative corrections of the CDM-2 collaboration and a resulting change in $\Delta\alpha_{had}^{(5)}$ of 20 % of its error was reported as a preliminary result at this conference [6].