Global Electroweak Fits and the Higgs Boson Mass

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The current electroweak data and the constraints on the Higgs mass are discussed. Within the context of the Standard Model the data prefer a relatively light Higgs mass.

I. PRECISION ELECTROWEAK DATA

This report contains an update on the values of the precision electroweak properties and fits within the context of the Standard Model (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, and from the SLD experiment at SLAC. All the LEPI results at the Z-pole are final [2]. The p̅p̅ results come from the CDF and D0 experiments at the Tevatron, using integrated Run 2 luminosities of up to 2.8 fb⁻¹.

The Z-lepton couplings (see [1, 2] for definitions and details) are extracted from the τ polarisation (A_τ, A_τ), the SLAC polarised electron asymmetry A_LR (A_τ) and the forward-backward asymmetries for leptons (A_ℓℓ, ℓ=e,μ,τ). The results are reasonably compatible with lepton universality and, assuming this, give A_τ = 0.1501 ± 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 ± 0.0083, which is 1.9 σ below 3.

In addition to these results, which involve only the Z-lepton couplings, there are also results involving Z-quark couplings. There are six such heavy-flavour quantities used; namely, the partial hadronic branching ratios and pole forward-backward asymmetries for b and c quarks (R_b, R_c, A^0_{FB,b} and A^0_{FB,c}) and the quantities A_b and A_c, measured directly by the SLC using a polarised electron beam.

There are six determinations of the effective weak mixing angle, giving an average value sin²θ_{eff} = 0.23153 ± 0.00016 [1]. There is a long-standing and a posteriori observation that the value obtained from purely leptonic processes (sin²θ_{eff} = 0.23113 ± 0.00021) is some 3.2σ different to that obtained using heavy quarks (sin²θ_{eff} = 0.23222 ± 0.00027). This comes mostly from the 3.2σ difference between the SLD A_LR and the A^0_{FB} values. The heavy-flavour results favour a rather heavy Higgs boson. However, it is worth noting that the overall χ² probability for the compatibility of all 6 measurements is reasonable (3.8%).

The W boson is produced singly at the Tevatron (e.g. u + d → W⁺). The leptonic decays W → ℓν (with ℓ = e,μ) are used to determine the W mass and width, using the transverse mass, p_T^ν or p_T^ℓ. CDF have published a Run 2 measurement, using an integrated luminosity of ≃ 0.2 fb⁻¹, which gives m_W = 80.413 ± 0.048 GeV; the single most precise experimental value. The Tevatron average has been recently updated (see [3], where details and references can be found), using a more consistent treatment of the Run 1 uncertainties on pdf’s, electroweak corrections and the value of Γ_W at which m_W is determined. This is important because the measured m_W and Γ_W values have a significant correlation. The SM value of Γ_W has also been updated [4] to Γ_W = 2.093 ± 0.002 GeV, and the m_W values are given for this value of Γ_W. The updated Tevatron average is m_W = 80.432 ± 0.039 GeV.

At LEP2 the W bosons are pair-produced in e⁺e⁻ → W⁺W⁻. The individual results from the four experiments are final and published, but the combination process is still preliminary. The statistical uncertainties from the ℓνq̅q̅' and q̅q̅'q̅q̅' channels are similar. The Final State Interaction (FSI) uncertainties, which include non-perturbative colour reconnection (CR) and Bose-Einstein Correlation (BEC) effects in the q̅q̅'q̅q̅' final state, and which lead to ‘cross-talk’ between the two W bosons, are still under study. At present a sizeable (∼ 36 MeV) common uncertainty is used, and this means that the q̅q̅'q̅q̅' channel has only a 22% weight in the combination with the ℓνq̅q̅'. The preliminary LEP2 value is m_W = 80.376 ± 0.033 GeV [5]. This is uncorrelated with the Tevatron measurement, and combining all these gives m_W = 80.399 ± 0.025 GeV. This value corresponds to a rather light Higgs boson in the context of the SM.

The Tevatron W width, which includes a preliminary D0 and a published CDF value from Run 2, has also been...
updated [3], giving $\Gamma_W = 2.050 \pm 0.058$ GeV. For LEP2, the FSI uncertainty is still preliminary and the current preliminary LEP combined value is $\Gamma_W = 2.196 \pm 0.083$ GeV. Together these give a revised World Average of $\Gamma_W = 2.098 \pm 0.048$ GeV, compatible with the SM expectation [4].

In the SM the top quark decays mainly as $t \to Wb$. The CDF and D0 Collaborations have continued to improve the precision on the top-quark mass, using up to 2.8 fb$^{-1}$ of Run 2 data and a variety of methods. The most precise values come from the $t\bar{t} \to b\bar{b}q\bar{q}\nu\bar{\nu}$ final state. The uncertainty in the jet energy scale (JES) is the largest potential systematic effect and this is reduced by simultaneously fitting to $m_t$ and a multiplicative JES factor, such that the $q\bar{q}$ invariant mass is constrained to the well-known value of $m_W$. The updated average value (see [3], where details and references can be found) is $m_t = 172.4 \pm 0.7$ (stat) $\pm 1.0$ (syst) GeV. This gives a total uncertainty of 1.2 GeV, a relative precision of 0.7%. The experimental values of $m_t$ extracted correspond to those used in the various Monte Carlo simulation programs. At present, any potential common systematic uncertainties associated with non-perturbative QCD effects (e.g. colour reconnection) are not included.

II. ELECTROWEAK FITS

The SM parameters required for the electroweak fits are $M_Z$, $G_F$, $\alpha(M_Z)$ and $\alpha_s(M_Z)$, (the electromagnetic and strong coupling constants at the scale $M_Z$), and the top-quark mass $m_t$. Through loop diagrams, measurements of the precision electroweak quantities are sensitive to $m_t$ (quadratically) and, to the ‘unknown’ in the SM, $m_H$ (logarithmically). The SM computations use the programs TOPAZ0 and ZFITTER (for more details see [1]). The latter program (version 6.42) incorporates the fermion 2-loop corrections to $\sin^2\theta_{\text{eff}}$ and full 2-loop and leading 3-loop corrections to $m_W$ [3].

The value of $\alpha$ at the scale $M_Z$ 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 $\alpha(M_Z)$ differ in the extent to which perturbative QCD is used, as well as in the data sets used in the evaluation. The quantity needed is the hadronic contribution from the 5 lightest quarks $\Delta\alpha_{\text{had}}^{(5)}$, and the value used by the LEP EWWG [1] is $\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02758 \pm 0.00035$ [4].

New data, since the publication of [1], particularly preliminary data from BES, could have a sizeable influence on both the central value and uncertainty. So finalisation of these BES results could have an important influence on the results of the electroweak fits. It is worth noting that the present uncertainty on $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$ corresponds to $\delta m_H/m_H \simeq 20\%$.

The 17 measurements used in the global SM electroweak fits, and the corresponding fitted values, are shown in fig. 1. The SM fit to these high $Q^2$ data gives

$$m_t = 172.5 \pm 1.2 \text{ GeV}$$
$$\alpha_s(M_Z) = 0.1185 \pm 0.0026$$
$$m_H = 84^{+34}_{-26} \text{ GeV},$$

with a $\chi^2$/ndf of 17.2/13; a probability of 19%.

The variation of the fit $\chi^2$, compared to the minimum value, is shown in the ‘blue-band’ plot of fig. 1 as a function of $m_H$. Also shown is the direct SM Higgs search limit of 114 GeV from LEP2 searches. The one-sided 95% upper limit is $m_H \leq 154$ GeV. This includes the theoretical uncertainty (blue-band), which is evaluated by considering the uncertainties in the 2-loop calculations [4]. If the more theory-driven value $\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02749 \pm 0.00035$ [3] is used, then the fitted value of $m_H$ increases to 94 GeV. It is also interesting to note that there is now [8] a 95% exclusion limit from the Tevatron at around $m_H \simeq 170$ GeV.

Since the fits made in 2007 [1], the main change is from the new top-quark mass (previous value $m_t = 172.4 \pm 1.8$ GeV), resulting in an increase in $m_H$ of about 8 GeV with respect to [1].

The quantities on which improved experimental precision can be expected in the near future are $m_t$, $m_W$, and $\Delta\alpha_{\text{had}}^{(5)}$. The relative current sensitivity to these quantities can be estimated as follows. If the central value of $m_t$, which is input to the fit, is changed by $\pm 1\sigma$ (i.e. $\pm 1.2$ GeV), then the corresponding shifts in the fitted values of $m_H$ are $+9$ GeV and $-8$ GeV respectively. Similarly, for $\pm 1\sigma$ changes in $m_W$ (i.e. $\pm 25$ MeV), the corresponding
FIG. 1: Left: The measured and fitted values, together with the pull values. Right: The ‘blue-band’ plot showing the variation of $\chi^2$ as a function of $m_H$. The region excluded by the direct SM Higgs search at LEP2 is also shown.

shifts in the fitted values of $m_H$ are -13 GeV and +17 GeV respectively. For ±1 σ changes in $\Delta \alpha^{(5)}_{\text{had}}$ (i.e. ±0.00035), the corresponding shifts in the fitted values of $m_H$ are -15 GeV and +17 GeV respectively. So it can be seen that improving the precision of $m_W$ and $\Delta \alpha^{(5)}_{\text{had}}$ is particularly important.

Comparison of the direct versus indirect values of $m_t$ and $m_W$ is a powerful test of the SM; see fig. 2. This method of presenting the electroweak data was first formulated in [9]. The contours shown are for the 68% cl. It can be seen that there is a reasonable degree of overlap and that both the direct and indirect data prefer a light Higgs mass. Indeed, the region preferred by the data corresponds to that expected in MSSM SUSY models.

It is of interest to consider the effect of the future improved precision which can be expected from the Tevatron. Assuming that the uncertainty on $m_t$ can be reduced from 1.2 to 1.0 GeV, and that the uncertainty on the World Average value of $m_W$ can be reduced from 25 to 15 MeV, then, if the central values of all measured quantities remain the same, the fitted Higgs mass would become

$$m_H = 71^{+24}_{-19} \text{ GeV},$$

with a one-sided 95% upper limit of 117 GeV. That is, this limit would not be far from the direct exclusion limit from LEP2. So the improved precision might lead to the interesting situation where the results would be in conflict with the SM.

III. SUMMARY

The current electroweak data severely constrain the Standard Model and prefer a relatively light Higgs boson mass. Improvements in the accuracy of the measurements used in the extraction of $\Delta \alpha^{(5)}_{\text{had}}$ are important. The improved precision on both $m_t$ and $m_W$ expected from the Tevatron, and then the LHC, is easily awaited.
FIG. 2: 68% contours for $m_t$ versus $m_W$ for both direct (solid line) and indirect measurements (dashed line). The corresponding Higgs mass values are also shown.

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