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Indirect bounds on the Higgs boson mass from precision electroweak data

John Ellis ^(a), G.L. Fogli ^(b) and E. Lisi ^(a,b)

^(a) *Theory Division, CERN, Geneva, Switzerland*

^(b) *Dipartimento di Fisica di Bari, Bari, Italy
Sezione INFN di Bari, Bari, Italy*

Abstract

We discuss the masses of the top quark and of the Higgs boson in the light of the available precision electroweak data, considering the latest LEP data as well as the latest CCFR measurements of $\nu\mathcal{N}$ and the SLC measurement of the left-right polarization asymmetry. The high precision reached by the experiments makes now possible to observe for the first time some discrepancies between different sets of data. In particular, the values of m_t indicated by different subsets of data differ by about 1.3 standard deviations, and the present direct experimental limit on the Higgs mass is somewhat higher than the indirect indications about its mass from the radiative correction effects. Ignoring these discrepancies, we find $m_t < 155$ GeV, $M_H < 250$ GeV, each at the 95% confidence level, from the precision electroweak data alone.

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It was pointed out several years ago [1] that precision electroweak data would furnish indirect information about unseen particles, especially the top quark and the Higgs boson of the Standard Model, although the sensitivity to m_t (quadratic) was greater than that to the latter (logarithmic). Even before LEP came into operation, earlier low energy experiments and $p\bar{p}$ collider measurements of M_W and M_Z provided an interesting upper bound on m_t [2]. The first LEP measurements supplemented this with a lower bound on m_t [3], leaving an allowed band which has become narrower with the improving precision of the LEP measurements [4].

Initially, our ignorance of M_H was not an important source of uncertainty, but this has now become as large as that associated with the experimental errors. We have therefore been led to investigate whether the data give any indications on M_H itself. We have presented previous analyses of M_H , showing χ^2 curves as functions of M_H , and χ^2 contours in the (M_H, m_t) plane [3], [5], [4]. They have always indicated that a low central value of M_H was preferred, although initially not with a high degree of significance. However, this tendency has accentuated over time, whilst the lower limit on M_H from direct searches at LEP has increased steadily, and is now 62.5 GeV at the 95% C.L. [6]. The question arises whether present electroweak data set a significant upper limit on M_H .

In this paper, we analyze this question in the framework of an updated global analysis of precision electroweak data. The most important development since our last analysis is the impressive improvement reached by the LEP data: we incorporate in our analysis the most recent high-precision determination of M_Z , as well as the updated measurements of the other Z peak parameters, including Γ_Z , σ_h^0 , $R = \Gamma_h/\Gamma_\ell$, the forward-backward asymmetries for leptons and b quarks, A_{FB}^ℓ , A_{FB}^b , the τ polarization data A_τ^{pol} and the most recent measurements of the hadronic partial widths $\Gamma(Z \rightarrow b\bar{b})$ and $\Gamma(Z \rightarrow c\bar{c})$ [7], [8]. Also included are the CCFR data on the ratio of neutral to charged current events in deep-inelastic $\nu\mathcal{N}$ and $\bar{\nu}\mathcal{N}$ scattering [9], [10], and the

first measurements of the left-right polarization asymmetry A_{LR} from the SLC [11]. Finally, we have also included in our global fit the latest values of $\sin^2 \vartheta_W$ extracted from $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering data [12]. The main theoretical update in our analysis is the $O(\alpha_s^2)$ calculation of A_{FB}^b [13]. We have not included the $t\bar{t}$ threshold correction of ref. [14], because they are small unless $m_t \geq 200$ GeV, and the treatment of $\Delta\kappa$ parallel to those available of Δr and $\Delta\rho$ is lacking as yet.

We find that two nagging discrepancies are revealed by the increased precision of the electroweak data, principally from LEP. One is that different sets of Z peak observables, namely the width and asymmetry measurements, favour values of m_t that differ by about 1.3 standard deviations. The other is that the preferred value of M_H is now about 1.4 standard deviations below the present direct experimental lower limit. Neither of these discrepancies is really worrying, and could well diminish or disappear with higher statistics. However, either discrepancy could be a signal for new physics if it grows in the future. Ignoring these discrepancies, we find $m_t < 155$ GeV, $M_H < 250$ GeV, each at the 95% confidence level, from the precision electroweak data alone.

Figure 1 contains the χ^2 analysis of the top quark mass. As far as QCD corrections are concerned, we fix $\alpha_s(M_Z) = 0.123 \pm 0.006$ [15]. In Fig. 1a we show, at fixed $M_H = M_Z$, the χ^2 behaviour as a function of m_t for different sets of measurements, as indicated. Individual measurements favour rather different ranges of m_t , this effect, not new in itself, being enhanced by the present precision of the experiments. The most marked difference comes from the comparison between widths (Γ_Z , σ_h^0 , $R = \Gamma_h/\Gamma_\ell$, $\Gamma_{b\bar{b}}/\Gamma_h$, $\Gamma_{c\bar{c}}/\Gamma_h$, indicated as WID + M_Z) and asymmetries (A_{FB}^ℓ , A_{FB}^b , A_τ^{pol} , A_{LR} , indicated as ASY + M_Z): the former family, dominated by the total width Γ_Z , favours a relatively low top quark mass, the latter clearly suggests (in particular the LEP measurements) a value of m_t 1.4 standard deviations larger (*). Intermediate values of m_t are indicated by the other data, vector boson masses ($M_W + M_Z$) and low energies (LE), whose present precision, however, is now definitely lower than that of the LEP

(*) This discrepancy, evidenced here at $M_H = M_Z$, cannot be solved varying M_H within the interval allowed by the present experimental limit. It can be only slightly diminished if M_H is taken around 10 GeV.

data. In this regard, we note an increase by ~ 20 GeV in the value of m_t predicted by the LE sector with respect to our previous analysis [5], due to the inclusion of the most recent measurement of CCFR [10], which is at present the most precise one in the ν - q sector and prefers larger values of m_t (*).

Of course, from the whole data set (ALL in Fig. 1a) we extract a very precise estimate of m_t at $M_H = M_Z$:

$$m_t = 140^{+17}_{-19} \text{ GeV} \quad \text{for } M_H = M_Z, \quad (1a)$$

but for the first time, due to the improved precision, we see a significant dispersion in the indications coming from the different subsets of data, even though it is too early to say whether the possible discrepancies could be induced by physical effects.

Figure 1b shows the χ^2 behaviour *vs.* m_t of the whole data set for different choices of M_H . The favoured value of m_t increases with M_H . By taking the envelope of the different curves, we derive limits on m_t which are independent of M_H . From Fig. 1b it follows in fact:

$$m_t = 132^{+20}_{-22} \text{ GeV} \quad \text{independently of } M_H. \quad (1b)$$

We can also derive a 95% C.L. upper limit on m_t ,

$$m_t < 155 \text{ GeV} \quad \text{at 95\% C.L., independently of } M_H, \quad (2)$$

which should encourage CDF [17] and D0 [18] in their challenging searches for the top quark. Our impression is that they are not too far from their goal.

(*) For the first time, in our approach to the estimate of the four squared chiral couplings we have also included the uncertainty in m_c , as derived from the analysis of the dimuon data performed by the CCFR Collaboration [16].

In Fig. 2 we introduce the $\alpha_s(M_Z)$ dependence. In Fig. 2a, contours of χ^2 are shown in the (m_t, α_s) plane for $M_H = M_Z$, which confirm that m_t and $\alpha_s(M_Z)$ are essentially uncorrelated. The precision electroweak data by themselves yield $\alpha_s(M_Z) = 0.127 \pm 0.006$, which is comfortably consistent with the LEP jet value of 0.123 ± 0.006 , used in the previous analysis at $\alpha_s(M_Z)$ fixed. It is encouraging that the long-standing discrepancy between the total e^+e^- cross-section and other determinations of $\alpha_s(M_Z)$ has now gone. In Fig. 2b, conversely, we draw the allowed regions in the plane (M_H, α_s) for m_t fixed at 140 GeV, showing a positive correlation between M_H and $\alpha_s(M_Z)$. We will discuss this point later.

Equipped with this background information, we are now ready to tackle the central issue of M_H . As for the top quark mass in Fig. 1, we report in Fig. 3 the behaviour of the χ^2 as a function of M_H . Fig. 3a shows this behaviour for m_t fixed at 140 GeV, as derived from the different sets of data. It is immediate to observe that the χ^2 's coming from boson masses ($M_W + M_Z$) and low energies ($LE + M_Z$) are very weakly dependent on M_H . This weak dependence was nevertheless relevant in the previous analyses: the limits on m_t derived by these two sets of data, essentially independent of M_H , were able to induce limits on M_H , because of the correlation between m_t and M_H introduced by the remaining set of data [4]. The present situation is different, the scene is dominated by the LEP data, whose behaviour we now discuss. Again, we find quite different behaviours of the sectors ($WID + M_Z$) and ($ASY + M_Z$): the latter puts a strong upper limit on M_H , but is unable to help in identifying a lower bound. A striking lower bound comes from ($WID + M_Z$), which however has a non-monotonic behaviour for M_H larger than 10 GeV. Of course, we can combine all these data, and we find the χ^2 denoted as ALL, at m_t fixed.

In Fig. 3b we report the overall χ^2 vs. M_H for different values of m_t . From the curves at higher m_t we see a distortion effect which signals the increasing importance of a second minimum due to the non-monotonic dependence of Γ_Z on M_H . We can, however, trace the envelope of the curves of Fig. 3b and derive a limit on M_H independent of m_t :

$$M_H = 10^{+25}_{-8} \text{ GeV} \quad \text{independently of } m_t. \quad (3)$$

We can also derive a 95% C.L. upper limit on M_H ,

$$M_H < 250 \text{ GeV} \quad \text{at 95\% C.L., independently of } m_t. \quad (4)$$

The above indications emerge in a clear way from the data, and the rather small value of M_H suggested by the analysis is, in our opinion, quite significant, in spite of the signalled distortion effect induced by Γ_Z . However, also in this case some problems arise: in fact, the present experimental limit on M_H found by the four LEP experiments combined together [6] is 1.4 standard deviations larger than the central value indicated in eq. (3). This difference is not by itself significant, and could be due to a statistical fluctuation, but is an indication that we are near to a true comparison between theory (here represented by the complex machinery of radiative corrections) and experiment (here dominated by LEP).

It is very probable that the present discrepancies in the m_t predictions of Fig. 1a and in the direct and indirect indications on M_H will in the future remain within the present acceptable limits, and tend to disappear eventually. In this case, the t quark is near to its discovery, and the Higgs boson has a relatively low mass, presumably compatible with that of a supersymmetric lightest neutral Higgs (and this is very remarkable point!). Otherwise, if the present discrepancies grow further, some other interpretations must be considered, not ascribed to statistics alone.

It is relevant at this point to discuss the relation between the “ M_H problem” and the value of $\alpha_s(M_Z)$. As already noticed, Fig. 2b shows a positive correlation between M_H and α_s . One could then wonder whether the “problem” could be solved if α_s were larger than indicated by LEP jet data. The figure shows that the central value of M_H could be increased to about 40 GeV if $\alpha_s = 0.133$, which is 1σ higher than the central value of 0.127 found in the global fit, and about 1.6σ higher than the central value of

0.123 indicated by LEP jet data. Thus, increasing $\alpha_s(M_Z)$ eases the “problem” but does not eradicate it (*).

In Fig. 4, finally, we consider the allowed regions in the plane (M_H, m_t) . Fig. 4a shows explicitly the limits we have given in eqs. (1–4). With dashed lines we show the same regions, excluding the low-energy (LE) contributions to the analysis. This gives an idea of the non-negligible relevance (less, however, than in the past) of these data. In Fig. 4a there is also a clear evidence of the distortion effects at high m_t and M_H induced by the non-monotonic dependence of Γ_Z on M_H . In order to eliminate this element of ambiguity, we have considered the same analysis *excluding* Γ_Z from the data. What follows is reported in Fig. 4b: on the one hand, we essentially lose the absolute lower limit on M_H , which “slides” to very low values not represented in the figure, but now we find a better behaviour of the χ^2 for M_H larger than 10 GeV. Again the data are consistent with a low Higgs mass, the limit from $(\text{ALL} - \Gamma_Z)$ being

$$M_H < 650 \text{ GeV}, \quad \text{at 95\% C.L., independently of } m_t. \quad (5)$$

Let us conclude with some further remarks concerning the present status of the precision electroweak data. The most important point is, in our opinion, that the precision reached by the experiments, firstly by LEP, is so high that the first discrepancies become to appear, induced by statistics or by some other reasons. This makes essential to use the *maximum accuracy* also in the analysis. In this regard:

- i) As far as the Higgs mass is concerned, we have chosen to emphasize the indirect indications coming from the analysis of precision electroweak data alone. The possible discrepancy with the direct limit is not yet worrying (1.4 standard deviations), but we cannot exclude the possibility that it could become significant in the future. We prefer to avoid combining direct and indirect limits using a penalty function

(*) We note in passing that the value of $\alpha_s(M_Z)$ inferred from LEP jet and low-energy data would indeed be increased if there was a light gluino weighting ≤ 5 GeV [19], but we do not necessarily advocate this possibility.

or a similar approach: this cannot be made in a convincing way, and , moreover, may only conceal any possible discrepancy between the two sources of information. Any such discrepancy may eventually be interpreted as a potential indication of new physics. It is clear, though, that the present data, if combined with the direct limit, would suggest that the Higgs mass is “just around the corner”.

- ii) The requirement of maximum accuracy contrasts with the use of some approximations in the estimate of the radiative correction effects. In particular, the use of any kind of simplification or approximate description such as $\sin^2 \theta_w^{\text{eff}}$ (see also the discussion of ref. [20]) induces a loss of precision unworthy of the present experimental precision.
- iii) We will not discuss in detail here the update of the model-independent three-parameter (S, T, U) or $(\varepsilon_1, \varepsilon_2, \varepsilon_3)$ analysis. The result is very similar to that presented in our previous papers on the subject [21], [4]. We only find a smaller ellipsoid in the three-parameter space. Its projection in the plane (S, T) , which is the most significant, is shown in Fig. 5. As before, we find that the Standard Model region has $\Delta\chi^2 \geq 1$ relative to the central value found in the three-parameter space. However, in our opinion, this $\Delta\chi^2 \simeq 1$ effect cannot be regarded as significant: in fact, it is reasonable to ascribe it to the increased number of degrees of freedom in the Standard Model analysis. In any case, we recall that the probability within the three-dimensional $\Delta\chi^2 = 1$ ellipsoid is only 20%. We conclude that the Standard Model gives a very good description of the full set of electroweak precision data. Any possible effects beyond it can only be small and probably cannot be seen in this model-independent approach, which has unavoidable uncertainties [21].

In conclusion, we may say that the analysis of precision electroweak data has now reached a very interesting stage. The LEP data are now dominant, but their higher precision is now beginning to reveal some nagging discrepancies. These are about 1.3 standard deviations in m_t , between the width and the asymmetry measurements, and about 1.4 standard deviations in M_H , between the central value preferred by the indirect analysis and the direct experimental limit. These are not yet significant, and only time

will tell whether they become so. Ignoring these possible discrepancies, we have quoted 95% confidence level upper limits on m_t and M_H (see eqs. (2) and (4), respectively) . They suggest that both these particles lie “just around” their respective corners. Again time will give to us the right answer.

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Figure captions

Fig. 1 – (a) At fixed $M_H = M_Z$, χ^2 curves as functions of m_t for different combinations of the precision electroweak data, including: $\nu - q$, $e - q$ and $\nu - e$ scattering data (LE), LEP measurements of widths (WID), LEP (dashed) and LEP+SLC (solid) measurements of Z^0 decay asymmetries (ASY), the ensemble of LEP data (LEP), LEP, SLC and $p\bar{p}$ collider data on M_W/M_Z (HE), and global fit (ALL).

(b) Global χ^2 curves, as functions of m_t , for different values of M_H .

Fig. 2 – (a) Central value and $\Delta\chi^2 = 1, 4, 9$ (1-, 2-, 3- σ) curves in the (m_t, α_s) plane with fixed $M_H = M_Z$. Also shown is the range $\alpha_s(M_Z) = 0.123 \pm 0.006$ inferred from measurements of hadronic final states.

(b) Central value and 1-, 2- and 3- σ curves in the (M_H, α_s) plane with fixed $m_t = 140$ GeV.

Fig. 3 – (a) At fixed $m_t = 140$ GeV, χ^2 curves as functions of M_H for different subsets of the electroweak data.

(b) Global χ^2 curves as functions of M_H for different choices of m_t .

Fig. 4 – (a) $\Delta\chi^2 = 1, 4, 9$ (1-, 2-, 3- σ) contours in the (M_H, m_t) plane for the full electroweak data set (solid lines) and for HE (LEP, SLC and collider) data alone (dashed lines).

(b) Same kind of contours, but excluding Γ_Z from the global fit.

Fig. 5 – Projection, onto the $(\delta\epsilon_1, \delta\epsilon_3)$ plane, of the ellipsoidal region allowed by electroweak data in the $(\delta\epsilon_1, \delta\epsilon_2, \delta\epsilon_3)$ space at the $\Delta\chi^2 = 1$ level. The standard model surface is bounded by the extreme points A, B, C, D, whose reference values in terms of (m_t, M_H) are (masses in GeV): $A \equiv (90, 1000)$, $B \equiv (250, 1000)$, $C \equiv (250, 50)$, $D \equiv (90, 50)$. The intermediate points correspond to $M_H = M_Z, 150, 300, 500$ GeV and to 20 GeV steps in m_t .

Fig. 1

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