Bounds on M_H from electroweak radiative corrections

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Sezione INFN di Bari, Bari, Italy***Abstract**

We report the results of a global fit to m_t and M_H within the Standard Model using the latest LEP and other precision electroweak data. We find $92 \text{ GeV} < m_t < 147 \text{ GeV}$ and $1.4 \text{ GeV} < M_H < 160 \text{ GeV}$ (68% C.L.) if all data are included, although the upper limit on M_H would be relaxed if (more conservatively) the troublesome measurements of the hadron-to-lepton ratio on the Z^0 peak are omitted from the fit. These ranges of m_t and M_H are consistent with the limits from direct searches, which is an impressive and non-trivial check on the consistency of the Standard Model beyond the tree level. Our analysis of radiative corrections disfavours a strongly-interacting Higgs system, as well as naïve $t\bar{t}$ condensate versions of the Standard Model. The top quark and the Higgs boson are probably both close to our present experimental reach.

ments of the elementary Higgs boson of the Standard Model by composite strongly-interacting systems such as technicolour [8] are tightly constrained by analyses similar to that of ref. [9].

The purpose of this paper is to update ref. [6] using the latest set of LEP [10], and other precision electroweak data [11], [12], presented at the Lepton-Photon & EPS High Energy Physics Conference held at the end of July 1991. In addition to the new data set, significant technical improvements have been included in this analysis. These include $O(\alpha_{\text{em}}\alpha_s)$ effects in the top and bottom contributions to vacuum polarization functions at high energies [13], a procedure for resumming higher orders in α_{em} [14], [15], and leading [16] and next-to-leading [17] QCD corrections to the hadronic Z^0 decay widths up to $O(\alpha_s^3)$. In point of fact, we find that including these effects does not greatly alter the preferred range of either m_t , M_H , or $\sin^2\theta_w$ extracted from the data.

We find an absolute minimum of the χ^2 in the (M_H, m_t) plane at $m_t \simeq 120$ GeV and $M_H \simeq 10$ GeV. The corresponding one-standard-deviation ranges of m_t and M_H separately (68% confidence level) are

$$92 \text{ GeV} < m_t < 147 \text{ GeV} \quad , \quad (1a)$$

$$1.4 \text{ GeV} < M_H < 160 \text{ GeV} \quad . \quad (1b)$$

The ranges (1) should be compared with the direct experimental limits $m_t > 89$ GeV from CDF [18], $M_H > 57$ GeV from LEP [19]. It is encouraging that the indirect bounds (1) are consistent with the direct searches, and suggest that these two Standard Model particles may be within experimental reach in the not-too-distant future.

We note that the limit (1b) corresponds to values of M_H in the region where perturbation theory can be expected to be reliable. Thus strongly-interacting Higgs systems now seem to be consistently disfavoured by the precision electroweak data. In particular this is the case of the naïve version of the $\bar{t}t$ condensate version of the Standard Model [20] with $m_t \simeq (200 \text{ to } 250)$ GeV and $M_H \simeq (1 \text{ to } 2)m_t$.

Complete descriptions of the assumptions and procedures used in our analyses of precision electroweak data including radiative corrections have been given previously

Several years ago already, experimental measurements of the electroweak interactions reached the precision required to be sensitive to radiative corrections. These depend on the masses of unseen virtual particles such as the top quark and the Higgs boson expected in the Standard Model [1]. Data available from laboratory experiments before LEP were thus able to impose interesting upper bounds on the top quark mass (m_t) [2], and first indications about its expected value [3], [4]. The precise measurements of the Z^0 mass (M_Z) at LEP and elsewhere enabled the previous upper limit on m_t to be converted into a relatively narrow allowed range [5], which has been further restricted by other accurate measurements of Z^0 decays at LEP [6] (see also refs. [7]).

The pre-LEP measurements were insensitive to the mass of the Higgs boson, but the advent of precise LEP data, combined with the other data, has begun to exhibit some sensitivity to M_H . This was apparent already using the LEP data available in mid-1990. The preferred value and one standard deviation range of m_t depended on M_H , as did the value of χ^2 at the preferred value of m_t . Conversely, for any given value of m_t , there was a finite range of values of M_H for which $\Delta\chi^2 \leq 1$. Overall, the 68% confidence level range for M_H was $1.8 \text{ GeV} < M_H < 6 \text{ TeV}$ [6]. This lower limit was not as strong as that available from direct searches for a Higgs boson at LEP (although more stringent than other reliable direct searches), and the upper limit on M_H was in a region where perturbation theory could not be relied on for the Higgs sector. Nevertheless, the 1990 result indicated the feasibility of bounding M_H using radiative corrections.

The possibility of bounding M_H as well as m_t arises from the fact that the LEP and other precise electroweak data are together sensitive to different combinations of the gauge boson vacuum polarization functions and to non-oblique (vertex and box) corrections, which within the Standard Model have different dependences on M_H and m_t . Thus values, or at least ranges, can be extracted for these two unknown parameters, and information obtained on possible physics beyond the Standard Model. Indeed, replace-

[4], [5], [6]. Here we just summarize features that have been included in our analysis for the first time.

At the one-electroweak-loop level $O(\alpha_{\text{em}})$, the precision high-energy measurements at LEP and $p\bar{p}$ colliders are sensitive to various combinations of gauge boson vacuum polarizations. The important (t, b) contributions to these vacuum polarizations have now been calculated including the leading strong interaction corrections, i.e. to $O(\alpha_{\text{em}}\alpha_s)$ [13], and it has been noted that these two-loop corrections make contributions to Δr , for example, that are comparable with those of $O(\alpha_{\text{em}})$ Higgs boson loops [15]. For some corrections, in particular in the estimate of Δr , not only the $O(\alpha_{\text{em}}\alpha_s)$ contributions, but specific prescriptions for resumming $O(\alpha_{\text{em}}^2\alpha_s^2)$ have been proposed [14], [15]. However, a consistent extension of this procedure to all the radiative corrections important for LEP has not been published.

We have included the $O(\alpha_{\text{em}}\alpha_s)$ (t, b) diagrams in the analysis of the high energy data reported in this paper. We have found that it is important to include consistently these procedures in the analysis of the high-energy data by applying them simultaneously to all the oblique corrections: the comparison of the different experimental quantities is in fact extremely sensitive to small modifications, because of the similar behaviours as a function of m_t of the values of $\sin^2\vartheta_w$ extracted from each of them. However, if all the $O(\alpha_{\text{em}}\alpha_s)$ corrections are included consistently, we find *not only*, as expected, that the preferred range of M_H is not very different from an $O(\alpha_{\text{em}})$ analysis, *but also* that the preferred range of m_t is not very different from that extracted in $O(\alpha_{\text{em}})$, being shifted upwards by less than 10 GeV. This is an encouraging check on the stability of our results with respect to refinements in the theoretical calculations.

We have not included $O(\alpha_{\text{em}}\alpha_s)$ effects in the analysis of low-energy data, since these have not all been calculated and there are unresolved tricky questions with regard to the choice of effective renormalization scale used to specify α_s . On the other hand, the comparison of low-energy and high-energy data, which have a very different behaviour in terms of m_t , is not influenced by the inclusion of the $O(\alpha_{\text{em}}\alpha_s)$ corrections in the recursion procedure [6]. Hence it is possible to combine the low-energy data analyzed together consistently in $O(\alpha_{\text{em}})$ with the high-energy data analyzed together consistently in $O(\alpha_{\text{em}}\alpha_s)$ as discussed above.

We now discuss the data set used in this analysis, which we take from presentations at the Lepton-Photon & EPS High Energy Conference held at the end of July 1991. The low-energy data that we use are little changed from those we have used previously, and the analysis assumptions are the same. The data include information on effective $\nu - q$ neutral current interactions, mainly obtained from deep-inelastic scattering $\nu N \rightarrow \nu X$ [3], on effective $e - q$ neutral current interactions, which is still dominated by the Boulder experiment on parity violation in Cesium [21], and on $\nu - e$ scattering. The only new feature in the low-energy data is from the CHARM II collaboration, who now measure simultaneously the cross-sections for $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering and derive the two couplings [11]

$$\begin{cases} g_V^e = -0.025 \pm 0.014 \pm 0.014 \\ g_A^e = -0.503 \pm 0.007 \pm 0.016 \end{cases} . \quad (2)$$

Within the Standard Model at the tree level, these results correspond to [11]

$$\sin^2\vartheta_w = 0.237 \pm 0.007 \pm 0.007 . \quad (3)$$

Including radiative corrections at the one-loop level, the extracted value of $\sin^2\vartheta_w$ decreases with increasing m_t in a manner similar to the value of $\sin^2\vartheta_w$ extracted from the $e - q$ data. Requiring compatibility between the value of $\sin^2\vartheta_w$ extracted from the $\nu - e$ and $e - q$ sectors and that coming from the $\nu - q$ analysis, which is much less dependent on m_t , imposes an upper bound on m_t , as can be seen in Fig. 1 which shows the χ^2 curves for the low-energy and other sectors of data (a more explicit description of the behaviour of the low-energy sector can be found in Fig. 1 of ref. [6]). For $M_H = M_Z$ the low energy data yield

$$m_t < 165 \text{ GeV} \quad 68\% \text{ C.L.} , \quad (4)$$

and this upper bound is insensitive to M_H . Sensitivity to M_H comes from combining the low-energy data with the high-energy data from LEP and $p\bar{p}$ colliders, as well as from consistency among the different high-energy measurements. The UA2 and

CDF collaborations have presented [12] new determinations of M_W/M_Z , which can be combined to give [12]

$$\text{UA2 + CDF :} \quad \sin^2 \theta_w = 1 - M_W^2/M_Z^2 = 0.2275 \pm 0.0052 \quad . \quad (5)$$

We take our LEP data set from the presentation of the 4 Collaborations at the Lepton-Photon & EPS High Energy Physics Conference [10]. The LEP data that we use as input are those coming from the lineshape, i.e. M_Z , Γ_Z , σ_h^0 , $R = \Gamma_h/\Gamma_t$, the partial widths $\Gamma_{b\bar{b}}$, $\Gamma_{c\bar{c}}$, and the recent determinations of the asymmetries $A_{\text{FB}}^e, A_{\text{FB}}^b, A_{\text{FB}}^c$. A global analysis including all these data requires knowledge of the error correlation matrix for those measurements which are correlated. The correlation matrix for the data of each collaboration is in principle different, and the correlation matrix for the LEP averages is not available. However, it has been found [10] that similar results are obtained using any one of the collaboration's correlation matrix. Here we use the ALEPH correlation matrix [22].

The χ^2 behaviours for different subsets of the high-energy data (M_Z and M_W/M_Z , all LEP data, all LEP data and M_W/M_Z) are shown in Fig. 1 as functions of m_t for $M_H = M_Z$. From these we find

$$M_Z \text{ and } M_W/M_Z : \quad m_t = 132 \quad {}^{+45}_{-49} \text{ GeV} , \quad (6a)$$

$$\text{all LEP data :} \quad m_t = 145 \quad {}^{+43}_{-55} \text{ GeV} , \quad (6b)$$

$$\text{all LEP and } M_W/M_Z : \quad m_t = 138 \quad {}^{+32}_{-38} \text{ GeV} , \quad (6c)$$

for $M_H = M_Z$. The full set of high-energy data can be combined with the full set of low-energy data also shown in Fig. 1 to yield

$$\text{all data :} \quad m_t = 130 \quad {}^{+25}_{-28} \text{ GeV} , \quad (7)$$

for $M_H = M_Z$.

Two comments on the global χ^2 behaviour and on that for LEP data are in order. One is that we have included theoretical errors in the inference of Δr from the LEP measurements of M_Z , due to the uncertainty in the extrapolation of α_{em} from the Thompson limit to M_Z (± 0.0009) [23] and allowances made for uncertainties related to the choices of the renormalization scheme [24] and of the α_s scale [25]. These have the effect of broadening the χ^2 curves for LEP data (by amounts ${}^{+5}_{-10}$ GeV at $\Delta\chi^2 = 1$ for the full data set), which in turn leads to a slightly lower central value of m_t ($\simeq -4$ GeV) when the LEP data are combined with other data in the global fit, because the LEP data have slightly less relative weight. The second comment is that the effect of including $O(\alpha_{\text{em}}\alpha_s)$ effects has been to increase the central value of m_t extracted from the LEP data, and the central value of the global fit to m_t , of about 6 GeV. While significant, these shifts are both considerably smaller than the overall errors in m_t , indicating that our results are likely to be stable with respect to further refinements in the theoretical analysis of these data.

Even though the LEP data by themselves now give a much sharper determination of m_t (6b) than was possible in 1990, the result (7) of the global fit is not greatly improved for fixed $M_H = M_Z$. However, the data are now much more sensitive to M_H , which is the main new message of this paper that we now discuss.

Fig. 2 shows the global χ^2 curves as functions of m_t for different values of M_H . We see that the preferred value of m_t increases slightly with increasing M_H . We also note that the value of χ^2 at the minimum increases as M_H is increased from about 10 GeV. This increase in χ^2 is much more pronounced than in the 1990 analysis [6]. The envelope of these χ^2 curves is the global χ^2 for m_t with M_H unconstrained. The absolute minimum of χ^2 occurs for $m_t = 120$ GeV and $M_H = 10$ GeV, and the $\Delta\chi^2 = 1$ line gives the 68% confidence level range

$$\text{all data :} \quad m_t = 120 \quad {}^{+27}_{-28} \text{ GeV} , \quad (8)$$

for M_H unconstrained.

It is also clear that this analysis can be made with the rôles of m_t and M_H inter-

changed. Fig. 3 shows the χ^2 curves as functions of M_H for $m_t = 130$ GeV. We see that the low-energy data by themselves are insensitive to M_H , whilst combining them with the LEP measurement of M_Z gives small sensitivity to M_H . The main sensitivity to M_H comes from consistency among the different pieces of LEP data. The global χ^2 is minimized when $M_H = 10$ GeV, and gives

$$1.3 \text{ GeV} < M_H < 160 \text{ GeV} \quad 68\% \text{ C.L.} , \quad (9a)$$

or

$$0.5 \text{ GeV} < M_H < 800 \text{ GeV} \quad 90\% \text{ C.L.} . \quad (9b)$$

for $m_t = 130$ GeV.

The global χ^2 curve is slightly distorted, and the reason can be traced to the LEP measurements of $R = \Gamma_h/\Gamma_e$. It is well-known that this measurement corresponds to a central value of α_s that is considerably higher than the range $\alpha_s = 0.115 \pm 0.008$ derived from event topology at LEP and adopted in our analysis [26], although the discrepancy is less than 2σ . However, when combined with the other LEP measurements, the value of R tends to drag the fit down to very low values of M_H , and the χ^2 behaviour is strongly influenced by this effect. Two extreme attitudes towards this behaviour are possible. One is to include the R data at face value, as we have done in eq. (9), and the other is to ignore them completely. In the latter case, the χ^2 is significantly reduced, is shifted to larger M_H and its behaviour looks more symmetrically curved. It is minimized when $M_H = 40$ GeV, and gives

$$2.6 \text{ GeV} < M_H < 500 \text{ GeV} \quad 68\% \text{ C.L.} , \quad (10a)$$

or

$$0.8 \text{ GeV} < M_H < 1600 \text{ GeV} \quad 90\% \text{ C.L.} . \quad (10b)$$

for $m_t = 130$ GeV.

Fig. 4 shows the global χ^2 curves as functions of M_H for different values of m_t . We see that the central value $M_H = 10$ GeV is relatively insensitive to m_t , although the

sensitivity to M_H is lost for larger values of m_t . Taking the envelope of these global χ^2 curves, we find

$$1.4 \text{ GeV} < M_H < 160 \text{ GeV} \quad 68\% \text{ C.L.} , \quad (11a)$$

or

$$0.5 \text{ GeV} < M_H < 1500 \text{ GeV} \quad 90\% \text{ C.L.} . \quad (11b)$$

for m_t left unconstrained.

The $\Delta\chi^2$ contours in the (M_H, m_t) plane are shown in Fig. 5 together with the location $m_t = 120$ GeV, $M_H = 10$ GeV of the minimum, to be compared with the direct experimental limits $m_t > 89$ GeV [18], $M_H > 57$ GeV [19]. We see that these contours are much more restrictive for large M_H than the one we published last year [6], although they are not very different on the (less interesting) side of small M_H . We are impressed by the fact that the indirect determinations of m_t and M_H via radiative corrections are consistent with the direct lower limits. We have not attempted to combine our indirect constraints on m_t and M_H with the direct bounds, e.g. by including a penalty function into our global fit, as this would require an analysis of the search data that goes beyond the scope of this paper. Nevertheless, the likely results of a constrained fit can be judged from the shape of the χ^2 's in Figs. 2, 4.

Naïve approaches [20] to the $t\bar{t}$ condensate version of the Standard Model require $m_t > 200$ GeV and $M_H > m_t$. This domain of parameter space is strongly disfavoured by our analysis.

Finally, we give the present value of the Standard Model parameter $\sin^2\theta_w$, extracted from the analysis of all data together. Taking $M_H = M_Z$ we find

$$\text{All}|_{M_H=M_Z} : \quad \sin^2\theta_w = 0.2277 \quad +0.0028 \quad -0.0027 , \quad (12)$$

for m_t unconstrained. The error is strongly reduced if we take m_t fixed, being now

$$\text{All} \quad \sin^2\theta_w = 0.2277 \pm 0.0004 . \quad (13)$$

for $M_H = M_Z$ and $m_t = 130$ GeV. An alternative definition of the weak mixing angle is $\sin^2 \hat{\theta}(M_Z)$, introduced as the $\overline{MS}$ running constant in ref. [27], which appears as the natural parameter in GUT's predictions. When derived from the present set of data, it exhibits a mild dependence on m_t . We find in fact

$$\text{All}|_{M_H=M_Z} \quad \sin^2 \hat{\theta}(M_Z) = 0.2327 \pm 0.0007, \quad (14)$$

where ± 0.00055 is the uncertainty to be ascribed to m_t .

Our analysis favours the optimistic possibility that not only the top quark but also the Higgs boson may lie close to our experimental reach. The top quark should be detectable at the FNAL $p\bar{p}$ collider. The Higgs sector of the Standard Model seems not to be strongly-interacting, and an elementary Higgs boson may well lie within the reach of LEP. If the Higgs boson of the Standard Model is indeed elementary, very likely it needs to be protected by supersymmetry against large radiative corrections to its mass. In the minimal supersymmetric extension of the Standard Model the highest CP-even Higgs boson is predicted to have a mass in the range $M_Z \pm 30$ GeV [28]. This range is completely consistent with our analysis of the Standard Model, and even favoured. However, a complete analysis of the precision electroweak data including radiative corrections calculated in the minimal supersymmetric extension of the Standard Model lies beyond the scope of this paper.

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

Fig. 2 — The χ^2 curves, as functions of m_t , for unconstrained global fits with different values of M_H . Note the increase in m_t and in the minimum of χ^2 as M_H is increased above 10 GeV.

Fig. 3 — The χ^2 curves as functions of M_H with fixed $m_t = 130$ GeV, for different combinations of the precision electroweak data. The notation is as in Fig. 1, with an extra curve (dashed) corresponding to the omission of LEP data on $R = \Gamma_h/\Gamma_t$ from the global fit.

Fig. 4 — The χ^2 curves as functions of M_H , for unconstrained global fits with different values of m_t . Note the minimum at $M_H \simeq 10$ GeV for $m_t < 150$ GeV.

Fig. 5 — The $\Delta\chi^2 = 1$ and 2.7 contours in the (M_H, m_t) plane for unconstrained global fits. Strongly interacting Higgses ($M_H \geq 1$ TeV) and naive $t\bar{t}$ condensate versions of the Standard Model ($m_t \simeq (200 \text{ to } 250)$ GeV and $M_H \simeq (1 \text{ to } 2)m_t$) are disfavoured. The solid lines are for all data, the dashed lines for all data with R omitted.