Updated prediction of the top quark mass and implications of its possible confirmation

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Abstract

Using the latest LEP and other precision data, we make what could be the last prediction of the mass of the top quark before its detection during the current Fermilab collider run: $m_t = 124^{+26}_{-28}$ GeV within the context of the Standard Model. We also predict that the Standard Model Higgs boson should weigh 25^{+275}_{-19} GeV. We present the implications for M_H and the parameters of the minimal supersymmetric extension of the Standard Model if indeed $m_t = 130$ GeV, and comment on the implications for the status of other proposed extensions of the Standard Model such as technicolour.

In the Standard Model, radiative corrections depend on the masses of unseen particles [1]. During the last few years, the increasing precision of electroweak data, of which the most important have been those from LEP, have made it possible to estimate indirectly the masses of the top quark and the Higgs boson of the Standard Model via their contributions to radiative corrections [2], [3]. The top quark has been predicted to have a mass close to the present experimental lower limit from the CDF collaboration [4], and the preferred range [3] of the Higgs mass has been below 300 GeV (more recently similar conclusions have been reached also in ref. [5]). It has also become possible to confront the precision electroweak data with proposed extensions of the Standard Model such as technicolour [6] and supersymmetric models [7]. The conclusions of this analysis disfavour technicolour models, but are consistent with the minimal supersymmetric extension of the Standard Model (MSSM), although it has not previously been possible to constrain its parameters significantly.

Recently, a new update of the precision LEP data has become available [8], and a new run of the Fermilab $p\bar{p}$ collider is starting. If the predictions based on precision electroweak data and radiative corrections are correct, the top quark should be discovered during this run. Indeed, one previous event consistent with $t\bar{t}$ and double semileptonic decay has been reported [4], and it is widely rumoured (and officially denied) that the CDF Collaboration has detected other events consistent with the production of a top quark weighing about 130 GeV. If this rumour were to be confirmed by subsequent data, it would be a wonderful confirmation of the theoretical framework of renormalization in gauge theories, and a vindication of precision experiments at LEP and elsewhere. Now is the moment to use the latest LEP data to make what may well be the *last* prediction of the top quark mass, and explore the implications of its possible confirmation for extensions of the Standard Model such as the MSSM.

We predict within the framework of the Standard Model that $m_t = 124^{+26}_{-28}$ GeV for M_H unconstrained. This range would be significantly increased if low-energy (LE) data — such as those from deep-inelastic scattering, ν -e scattering and parity violations in

atoms — were not combined with the high-energy (HE, mainly LEP) data. Correspondingly, we predict that the mass of the Standard Model Higgs boson would be in the range 6 GeV $< M_H < 300$ GeV at the 68% confidence level for m_t unconstrained, with a preferred value around 25 GeV. The upper limit on M_H would be significantly increased if the LE data were not included in the analysis, because of the strong correlation between the values of m_t and M_H and the higher range of m_t inferred from the HE data alone. For the inescapable reason mentioned in the previous paragraph, we then discuss the implications for the Higgs boson and the MSSM if indeed $m_t = 130$ GeV. We find $M_H = 30^{+180}_{-24}$ GeV in this case. We also present contours of χ^2 in the parameters space of the MSSM, in particular in the planes of values of the pseudoscalar Higgs mass and ratio of the Higgs v.e.v.'s ($m_A, \tan\beta$) and of the two mass parameters ($m_0, m_{\tilde{g}}$), where $m_{\tilde{g}}$ is the gluino mass and m_0 a common sfermion mass. We find a weak dependence of χ^2 on the Higgs parameters, but a significant extension of previous direct experimental bounds in the $(m_0, m_{\tilde{g}})$ plane. We also comment on the implications of the latest LEP data for proposed technicolour extensions of the Standard Model.

The basic principles and practical aspects of using precision electroweak measurements to constrain the masses of unseen particles indirectly via their radiative correction effects are well known, and we will not repeat them here. We start by discussing the latest constraints on m_t and M_H within the Standard Model, where we break no new theoretical ground. Technical details and assumptions used in our analysis have been documented previously [9], [2]. The main difference here is that we use the latest update of the LEP measurements including the full 1991 data set [8]. Collider and low-energy data are as in ref. [3], with $\alpha_s(M_Z^2) = 0.118 \pm 0.008$. As we shall discuss later, although the precision LEP data play a central rôle in constraining m_t , collider and low-energy data are also important, particularly for constraining M_H .

The updated χ^2 curves as functions of m_t for different choices of M_H are similar in form to those in ref. [3]. We infer from the envelope of these curves the following central and ± 1 standard deviation values of m_t :

$$\text{all data} \big|_{M_H \text{ free}} : \quad m_t = 124^{+26}_{-28} \text{ GeV}, \quad (1a)$$

$$\text{all data}|_{M_H=M_t} : \quad m_t = 132 \quad + 24 \quad - 26 \quad \text{GeV}, \quad (1b)$$

The global minimum of $\chi^2 \simeq 4.3$ is appreciably lower than in our previous analysis [3]. This is mainly because the updated measurements of $R = \frac{\Gamma_h}{\Gamma_t}$ on the Z^0 peak and of the forward-backward asymmetries (ASY) agree better with the other precision electroweak data.

If now in the analysis we treat $\alpha_s(M_Z^2)$ as a free parameter, we find the result shown in Fig. 1:

$$\alpha_s(M_Z^2) = 0.133 \pm 0.010 \quad (\text{if } M_H = M_Z) \quad (2)$$

(which corresponds to $280 \text{ MeV} < \Lambda_{\overline{MS}}^{(QCD)} < 660 \text{ MeV}$). The value (2) is not very different from the value $\alpha_s(M_Z^2) = 0.118 \pm 0.008$ inferred from analyses of event shapes in hadronic final states at LEP.

We remind the reader of the contribution to the χ^2 function which is made by the low-energy (LE) data. They provide an upper bound on m_t which is essentially independent of M_H , whereas the High-energy (HE) data by themselves exhibit a positive correlation between m_t and M_H . By combining the LE and HE data, we find a dependence on M_H of the minimum value of χ^2 which is stronger than that obtained from the HE data alone.

Fig. 2a shows the χ^2 curves as functions of M_H for different choices of m_t . The curves have concave forms for values of m_t in the preferred range (1). We infer from the envelope of these curves the following central and ± 1 standard deviation values of M_H :

$$\text{all data} : \quad M_H = 25 \quad + 275 \quad - 19 \quad \text{GeV}, \quad (3)$$

The contributions to χ^2 from different subsets of the electroweak data are shown in Fig. 2b for the choice $m_t = 130 \text{ GeV}$, which is motivated by the prediction (1) and the CDF rumours mentioned above. Here we see explicitly that the LE data are themselves

independent of M_H : however, they constrain M_H indirectly by not allowing a large value of m_t .

We exhibit in Fig. 3a the $\Delta\chi^2 = 1$ and 2.7 contours in the (M_H, m_t) plane for the full electroweak data set, and in Fig. 3b the $\Delta\chi^2 = 1$ and 2.7 contours for the HE data alone. We see explicitly that the $\Delta\chi^2$ contours are very similar for low values of M_H and m_t . However, the addition in Fig. 3a of the low-energy data truncates the contours in the region of high M_H and m_t , which would otherwise have been allowed by the HE data alone, as seen in Fig. 3b.

We now comment on the relation of the bounds (1), (3) to the direct search limits: $m_t > 91 \text{ GeV}$ from CDF [4] and $M_H > 59 \text{ GeV}$ from LEP [10]. The fact that the range (1) is consistent with the direct lower limit on m_t is an important and non-trivial consistency check on the calculability of the Standard Model at the level of one-loop and beyond. The range (1) suggests strongly that the top quark is within the reach of the current FNAL collider run. We see from Fig. 1a that for m_t to exceed 200 GeV, and hence lie beyond the reach of the FNAL collider, one would have to pay a price of $\Delta\chi^2 \geq 7$. We are not concerned that the minimum value of χ^2 occurs at a Higgs mass that is already excluded by the direct searches: for $M_H = 60 \text{ GeV}$ one need only pay a price $\Delta\chi^2 \simeq 0.2$. We have not attempted to combine the direct and indirect limits on m_t and M_H , preferring simply to compare these limits with those coming from radiative correction effects. We are encouraged that the largest probability density for M_H is in the region that can be explored by LEP 200. For M_H to exceed 1 TeV, and hence lie beyond the reach of LHC, one would have to pay a price of $\Delta\chi^2 \geq 2$. We do not resist the temptation of quoting a sharpened range of M_H if indeed $m_t = 130 \text{ GeV}$ as rumoured and denied. We infer from Fig. 2b that in this case

$$\text{All data}|_{m_t=130 \text{ GeV}} : \quad M_H = 30 \quad + 180 \quad - 24, \quad (4)$$

which is a modest reduction of the global range (3).

The range (3) or (4) is highly consistent with the theoretical estimate $M_H \leq 130 \text{ GeV}$ of the mass of the lighter CP-even Higgs boson in the minimal supersymmetric extension of the Standard Model (MSSM). However, an analysis of radiative corrections

within the MSSM requires the inclusion of many other particles, vertices and diagrams. We have published previously first analyses of the electroweak data incorporating vacuum polarization (oblique) one-loop diagrams with stops $\tilde{t}$ and sbottoms $\tilde{b}$ [11], and also of the full spectrum of MSSM Higgs bosons including one-loop radiative corrections to their masses [7]. Here we extend and update those analyses, incorporating all oblique one-loop diagrams involving sleptons, squarks, Higgs bosons, neutralinos and charginos, and using the latest electroweak data. We discuss in particular the constraints on the MSSM if indeed $m_t = 130$ GeV.

We take as the basic parameters of the MSSM, beside the top quark mass m_t , the common sfermion mass parameter m_0 , the gluino mass $m_{\tilde{g}}$, a Higgs superpotential mixing parameter μ , the ratio $v_2/v_1 \equiv \tan \beta$ of supersymmetric Higgs v.e.v.'s, the neutral CP-odd Higgs boson mass m_A , and the supersymmetry-breaking trilinear coupling parameter A_t . We derive from these the masses of the sneutrinos $\tilde{\nu}$, charged sleptons $\tilde{\ell}_{L,R}$, squarks $(\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b})_{L,R}$, mixed stops $\tilde{t}_{1,2}$, Higgses h, h' and $H^\pm$, neutralinos $\chi_{1,2,3,4}$ and charginos $\chi_{1,2}^\pm$, the mixing angles of the stops (θ_t) , neutral Higgs bosons (α) and Higgs couplings (ζ) , and the neutralino and chargino coupling matrices. Detailed definitions and formulae are reviewed elsewhere. Here we just quote the most relevant formulae for the neutrino, slepton and squark masses [12]:

$$m_{\tilde{g}}^2 = m_0^2 + \frac{1}{3} M_Z^2 \cos 2\beta + 0.06 m_{\tilde{g}}^2, \quad (5a)$$

$$m_{\tilde{t}_L}^2 = m_0^2 + (-\frac{1}{3} + s_w^2) M_Z^2 \cos 2\beta + 0.06 m_{\tilde{g}}^2, \quad (5b)$$

$$m_{\tilde{t}_R}^2 = m_0^2 + s_w^2 M_Z^2 \cos 2\beta + 0.01 m_{\tilde{g}}^2, \quad (5c)$$

$$m_{(\tilde{d}, \tilde{s}, \tilde{b})_L}^2 = m_0^2 + (\frac{1}{3} - \frac{2}{3} s_w^2) M_Z^2 \cos 2\beta + 0.83 m_{\tilde{g}}^2, \quad (5d)$$

$$m_{(\tilde{u}, \tilde{c})_R}^2 = m_0^2 + \frac{2}{3} s_w^2 M_Z^2 \cos 2\beta + 0.78 m_{\tilde{g}}^2, \quad (5e)$$

$$m_{(\tilde{d}, \tilde{s}, \tilde{b})_R}^2 = m_0^2 + (-\frac{1}{3} + \frac{1}{3} s_w^2) M_Z^2 \cos 2\beta + 0.83 m_{\tilde{g}}^2, \quad (5f)$$

$$m_{(\tilde{d}, \tilde{s}, \tilde{b})_R}^2 = m_0^2 - \frac{1}{3} s_w^2 M_Z^2 \cos 2\beta + 0.78 m_{\tilde{g}}^2, \quad (5g)$$

$$m_{\tilde{t}_{1,2}}^2 = \text{eigenvalues of } \begin{pmatrix} m_{\tilde{t}_L}^2 & m_{\tilde{t}_R}^2 \\ m_{\tilde{t}_R}^2 & m_{\tilde{t}_R}^2 \end{pmatrix}, \quad (5h)$$

with [12], [13]

$$m_{\tilde{L}_L}^2 = m_0^2 + m_t^2 + (\frac{1}{2} - \frac{2}{3} s_w^2) M_Z^2 \cos 2\beta + 0.83 m_{\tilde{g}}^2, \quad (6a)$$

$$m_{\tilde{R}_R}^2 = m_0^2 + (-\frac{1}{2} + \frac{1}{3} s_w^2) M_Z^2 \cos 2\beta + 0.78 m_{\tilde{g}}^2, \quad (6b)$$

$$m_{\tilde{L}_R}^2 = m_t \left(A_t + \frac{\mu}{\tan \beta} \right). \quad (6c)$$

The coefficients of the $m_{\tilde{g}}$ -dependent terms in (5) come from standard renormalization calculations in a minimal supersymmetric GUT, which is known to be highly consistent with the values of the Standard Model gauge couplings measured at LEP [14]. We also assume the GUT relations between $m_{\tilde{g}}$ and the SU(2) and U(1) gaugino mass parameters:

$$m_{\tilde{g}} : m_{\tilde{W}} : m_{\tilde{B}} = \alpha_s : \alpha_2 : \alpha_1. \quad (7)$$

Formulae for the one-loop oblique radiative corrections in the MSSM can be found in refs. [15].

To simplify our presentation of constraints on the MSSM, we concentrate here on two parameter planes: $(m_0, m_{\tilde{g}})$ and $(m_A, \tan \beta)$. As for the other basic parameters of the MSSM listed above, we assume here a fixed large value of μ , we use for illustration $m_t = 130$ GeV, and we set the largely irrelevant parameter $A_t = 0$. We will present elsewhere [16] constraints in the $(\mu, m_{\tilde{g}})$ plane and detailed discussions for other values of m_t .

We present in Figs. 4 the $\Delta\chi^2 = 1$ and 2.7 contours in the $(m_0, m_{\tilde{g}})$ plane for $m_t = 130$ GeV, $\mu = -300$ GeV, assuming $\tan \beta = 4$. The reference point in estimating the $\Delta\chi^2$ contours is the limit $m_0, m_{\tilde{g}} \rightarrow \infty$, where all sparticles decouple. Full (dashed) heavy lines indicate the limits coming from the analysis when the chargino and

neutralinos effects are (are not) included. These limits must be compared with the limit due to the direct decay into the lightest chargino with mass $M_Z/2$, represented by the heavy dashed line. Also shown is the excluded zone corresponding to $m_{\tilde{\nu}}^2 < 0$, in which the desired $\Delta L = 0$ electroweak vacuum would be unstable, together with the curves for constant $m_{\tilde{\nu}}$ and $m_{\tilde{g}}$. The $\Delta\chi^2 = 1, 2, 7$ contours are not at all sensitive to A_t , but somewhat sensitive to m_t, μ and $\tan\beta$, as we discuss elsewhere in detail [16]. We see that the radiative correction constraints on $(m_0, m_{\tilde{g}})$ are significantly more stringent than those from the direct searches, which is a novel and striking result. It is apparent that a plausible improvement in the precision of data from LEP I might even pre-empt the LEP 200 and FNAL collider discovery ranges.

We present in Fig. 5a the χ^2 curves as functions of m_A for $m_t = 130$ GeV and the 3 representative choices $\tan\beta = 2, 4, 8$, assuming $\mu = m_0 = m_{\tilde{g}} = 1$ TeV. We see that χ^2 becomes constant in the large m_A limit, and indeed takes the same value as in the Standard Model for M_H equal to the corresponding value of the lighter CP-even supersymmetric Higgs mass m_h . The minimum value of χ^2 occurs at a lower value of m_A , close to the present direct experimental limit. The value of χ^2 at this minimum is comparable to that in the Standard Model as shown in Figs. 1 and 2. Fig. 5b displays $\Delta\chi^2$ contours in the $(m_A, \tan\beta)$ plane for $m_t = 130$ GeV as usual. We see again the preference for $m_A \simeq 35$ GeV, but this preference is not very marked, and cannot yet be used to exclude any region of the $(m_A, \tan\beta)$ plane. The preference for $m_A \simeq 35$ GeV is insensitive to m_t , and become more (less) marked for $m_t < (>) 130$ GeV, as discussed in more detail in refs. [7], [16]. We see here that future precision data from LEP I could complement the LEP 200 and LHC discovery ranges for supersymmetric Higgs bosons.

We conclude with some comments updating our previous “model-independent” analysis [6] in terms of the (S, T, U) or equivalently $\varepsilon_{1,2,3}$ combinations of vacuum polarization parameters. Assuming $m_t = 130$ GeV and $M_H = M_Z$ to specify the vertex corrections and remove higher-order ambiguities, as discussed in ref. [6], we find that the contributions to $\varepsilon_{1,2,3}$ from beyond the Standard Model are

$$\delta\varepsilon_1 = (0.09 \pm 0.25) \times 10^{-2}, \quad (8a)$$

$$\delta\varepsilon_2 = (0.09 \pm 0.72) \times 10^{-2}, \quad (8b)$$

$$\delta\varepsilon_3 = -(0.24 \pm 0.38) \times 10^{-2}. \quad (8c)$$

We find from Fig. 6 that the intersection between the $\Delta\chi^2 = 1$ ellipsoid in the 3-parameter $\delta\varepsilon_{1,2,3}$ space and the two-dimensional submanifold attainable in the Standard Model for $90 \text{ GeV} < m_t < 250 \text{ GeV}$, $50 \text{ GeV} < M_H < 1 \text{ TeV}$ is greater than in our previous analysis [6]. This strengthens our previous finding that the Standard Model is acceptable, since one does not reduce χ^2 greatly by introducing a third parameter. This improved consistency reflects the fact that the central value (3) of M_H is somewhat higher than in our previous analysis. In the same Fig. 6, projected in the $(\delta\varepsilon_1, \delta\varepsilon_3)$ plane, we report the technicolour predictions for $N_C = 1$, which, according with our analysis [6], based on the estimates of refs. [17], is the most favorable scheme among those based on technicolour theories. The prediction is clearly still disfavoured by the data.

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Fig. 1 — Central value and $\Delta\chi^2 = 1$ curves in the $(m_t, \alpha_s(M_Z^2))$ plane for two different values of the Higgs mass: the solid and dashed ellipses correspond to $M_H = M_Z$ and $M_H = 300$ GeV, respectively. Also shown the range $\alpha_s(M_Z^2) = 0.118 \pm 0.008$ inferred from measurements in hadronic final states.

Fig. 2 — (a) The χ^2 curves as functions of M_H for different choices of m_t , including all data. (b) The contributions to χ^2 from different subsets of the electroweak data for the choice $m_t = 130$ GeV.

Fig. 3 — The $\Delta\chi^2 = 1, 2, 7$ contours in the (M_H, m_t) plane for (a) the full electroweak data set, and (b) the HE (LEP and collider) data alone.

Fig. 4 — The $\Delta\chi^2 = 1, 2, 7$ contours in the $(m_0, m_{\tilde{g}})$ plane of the MSSM, for $m_t = 130$ GeV, $\mu = -300$ GeV, $\tan \beta = 4$ and $m_A = 1$ TeV, shown as full heavy lines. The heavy dashed line is the limit due to the direct decay into the lightest chargino with mass $M_Z/2$. Dash-dotted heavy lines indicate the limits when the chargino and neutralino effects are not included. Also shown is the excluded zone corresponding to $m_{\tilde{g}}^2 < 0$, together with the curves for constant $m_{\tilde{g}}$ and $m_{\tilde{g}R}$.

Fig. 5 — (a) The χ^2 curves as functions of m_A for $m_t = 130$ GeV and $\tan \beta = 2, 4, 8$. (b) The χ^2 curves in the $(m_A, \tan \beta)$ plane for $m_t = 130$ GeV. Note that χ^2 becomes constant in the large m_A limit, and that a smaller value $m_A \approx 35$ GeV is slightly preferred.

Fig. 6 — Updated analysis in the 3-parameter $(\delta\epsilon_1, \delta\epsilon_2, \delta\epsilon_3)$ or $(\delta S, \delta T, \delta U)$ space. Note that the greater overlap of the $\Delta\chi^2 = 1$ experimental ellipsoid with the Standard Model submanifold, as compared to the analysis in ref. [6]. The data still disfavour the technicolour predictions (see [6]) even for the best case $N_C = 1$, shown projected on the $(\delta\epsilon_1, \delta\epsilon_3)$ plane.