The Top Quark and Higgs Boson Masses in the Standard Model and the MSSM

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Abstract

We update the precision electroweak prediction of m_t , making a global analysis including low-energy data as well as the latest LEP and SLC data, and compare it with the mass indicated by CDF measurements: theory and experiments match within errors. In view of the excellent agreement, we combine the information on m_t to sharpen indications on M_H , finding a central value around 100 GeV, in agreement with the prediction of the Minimal Supersymmetric extension of the Standard Model (MSSM). Our most complete fit gives $m_t = 162 \pm 9$ GeV, with M_H free. We also present bounds from precision electroweak data on the sfermion and gaugino masses in the MSSM, which are competitive with direct limits from CDF, and exclude charginos close to the present mass limits.

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The evidence presented by the CDF collaboration for production of the top quark [1] inaugurates a new era in the analysis of precision electroweak data. Before the CDF observation, precision electroweak data from LEP and elsewhere could be used, together with calculations of radiative corrections within the Standard Model [2, 3], to estimate the top quark mass m_t [4] with an accuracy of about 15% [5, 6, 7], and gave indications on the Higgs boson mass M_H [8, 9]. The CDF measurement of m_t , which has an accuracy of about 10%, agrees within the stated errors with the radiative correction estimate. This constitutes a major success for the theoretical framework of the Standard Model, namely renormalizable gauge theory.

This agreement between direct and indirect estimates of m_t can be used in at least two ways. One is to constrain further M_H , the one remaining parameter of the Standard Model. The other is to look for possible physics beyond the Standard Model or, more likely, constrain the parameters of such extensions. This paper explores both avenues, with particular emphasis on constraining the Minimal Supersymmetric extension of the Standard Model, the MSSM [10].

Besides the direct evidence for the top quark, recent months have witnessed several other interesting new relevant experimental developments. One has been the announcement of a new generation of LEP data [11, 12] with errors that are considerably reduced, as a result of increased statistics and the very accurate beam energy calibration that has been possible using transverse beam polarization [13]. Another has been the publication of a new, very precise measurement of the longitudinally-polarized beam asymmetry A_{LR} by the SLD collaboration working at the SLC [14]. There have also been other developments such as an improved measurement of M_W [15] and new electroweak results from the CDFR collaboration [16].

The analysis of this paper starts with a re-evaluation of the radiative-correction estimate of m_t and M_H , incorporating these measurements together with other data, principally at lower energies. Since the LEP collaborations explore themselves the implications of their data for m_t and M_H [6, 17], we give particular emphasis to the combination of their data with those of other experiments, reviewing in particular our treatment of low-energy data. It is encouraging that these and measurements of M_W give estimates of m_t that are consistent with that from LEP, and this global consistency strengthens the indications on M_H . However, it is well known that the SLD measurement of A_{LR} corresponds to a much larger range of m_t and, as we discuss later, a lower range of M_H . The discrepancy with the rest of the world's precision electroweak data is about 2.6 standard

deviations. This is at the boundary where the combination of A_{LR} with the other data is worrisome: we present the results of global fits with and without A_{LR} included¹

$$m_t = \begin{cases} \begin{matrix} +15 \\ -15 \end{matrix} & \text{GeV} \\ \begin{matrix} 153 \\ 150 \end{matrix} \end{cases}, \quad M_H = \begin{cases} \begin{matrix} +70 \\ -22 \end{matrix} & \text{GeV (with } A_{LR}) \\ \begin{matrix} +230 \\ -45 \end{matrix} & \text{GeV (without } A_{LR}) \end{cases} \quad (1)$$

The ranges of m_t reported above are highly consistent with that quoted by the CDF collaboration on the basis of their kinematic fits: $m_t = 174 \pm 16$ GeV [1], so this number can be combined in the global analysis to yield

$$m_t = \begin{cases} \begin{matrix} +11 \\ -12 \end{matrix} & \text{GeV} \\ \begin{matrix} 163 \\ 164 \end{matrix} \end{cases}, \quad M_H = \begin{cases} \begin{matrix} +110 \\ -32 \end{matrix} & \text{GeV (with CDF, } A_{LR}) \\ \begin{matrix} +380 \\ -95 \end{matrix} & \text{GeV (with CDF, not } A_{LR}) \end{cases} \quad (2)$$

In addition to the kinematic fits, the CDF collaboration has published [1] values for the $\bar{t}t$ cross section, as well as errors. Taken at face value, the $\bar{t}t$ cross section corresponds to a somewhat lower range of m_t , centred around 140 GeV, but the two measurements are compatible at the 12% confidence level with $m_t = 156 \pm 11$ GeV. Moreover, the D0 collaboration has also announced a value for the $\bar{t}t$ production cross section [18], which is lower than that quoted by CDF and compatible with zero. Combining their data with those from CDF, we find $m_t = 167 \pm 12$ GeV at an overall confidence level of 8%, which is also quite acceptable. Combining this in the global analysis, we find

$$m_t = \begin{cases} \begin{matrix} +9 \\ -9 \end{matrix} & \text{GeV} \\ \begin{matrix} 162 \\ 162 \end{matrix} \end{cases}, \quad M_H = \begin{cases} \begin{matrix} +95 \\ -28 \end{matrix} & \text{GeV (with CDF, D0, } A_{LR}) \\ \begin{matrix} +320 \\ -90 \end{matrix} & \text{GeV (with CDF, D0, not } A_{LR}) \end{cases} \quad (3)$$

which provides our best estimate of the Standard Model parameters. In the rest of this paper, we give more details on these results, and also discuss the implications of the recent data for the MSSM.

¹The LEP data alone give a weaker indication on M_H [17].

We start by presenting an analysis of the available precision electroweak data in the context of the Standard Model, discussing what one can say about m_t and M_H , with a view to subsequent confrontation and combination with the CDF evidence for the top quark. The central rôle in the electroweak data set is played by data on the Z^0 peak from LEP. An updated compilation of these data was recently presented at the La Thuile [11] and Moriond [12] conferences. We use the values reported there, including a revision of the LEP error on $R_b = \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{all})$ [17] (which reduces its discrepancy with the theoretical predictions to less than 2σ) but excluding the measurement of the forward-backward charge asymmetry for hadrons, pending clarification of its systematic theoretical uncertainty.

Another key experimental input is the SLD measurement of A_{LR} [14], the left-right asymmetry for hadron production with a polarized electron beam. This already constitutes a more precise determination of $\sin^2\theta_W^{\text{eff}}$ than any individual LEP measurement, and its precision is expected to improve significantly in the foreseeable future. However, as is well known, its combination with the other precision electroweak data presents certain problems, since its central value of $\sin^2\theta_W^{\text{eff}}$ is significantly different from that determined by LEP measurements. We take the view that since the discrepancy with other data is less than 3 standard deviations (the A_{LR} contribution to the χ^2 found in a global analysis is discussed in more detail below) there is no good reason to exclude *a priori* A_{LR} . However, we do present the results of global fits both including and excluding the A_{LR} measurement.

There has been significant progress recently in the measurement of M_W by the CDF and D0 collaborations, whose combined value we take from Ref. [15].

A particular feature of our precision analysis is the inclusion of a complete set of low-energy data [19]. These include measurements of ν - e scattering, determination of the low-energy effective e - q neutral current couplings including (but not exclusively) the measurements of parity violation in atoms, and determinations of the low-energy effective ν - q neutral current couplings that are derived from deep-inelastic ν - N scattering cross sections. In particular, the latter yield a value of $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$ that is in general not independent of m_t , (as assumed in some approximate treatments [17]). These data actually provide by themselves an upper bound on m_t [4, 19], but are essentially insensitive to M_H . One comment concerns the value of the charm quark mass m_c used in the analysis of deep-inelastic ν - N scattering data, which we take from the determination by the CCFR collaboration: $m_c = 1.31 \pm 0.24$ GeV [20]. We use this value consistently

in the analysis also of the other deep-inelastic $\nu\bar{\nu}$ scattering experiments, treating its uncertainty as a common systematic error.

Before presenting the results of our global fit, we record the value of $\alpha_s(M_Z)|_{\overline{\text{MS}}}$ we assume, namely the world average 0.118 ± 0.007 [21]. This is intermediate between values extracted from some low-energy experiments such as deep-inelastic scattering and quarkonia, and values extracted from LEP jet measurements [23]. We believe that there are significant uncertainties concerning higher-order perturbative QCD corrections [22] that should be reduced before the LEP jet measurements could become the most accurate determination of $\alpha_s(M_Z)|_{\overline{\text{MS}}}$. At present we think that the world average is more appropriate for use in a global electroweak analysis not limited to LEP data alone. We shall however briefly comment on the effect of varying the central value of $\alpha_s(M_Z)|_{\overline{\text{MS}}}$.

We present our results as contours of χ^2 in the (M_H, m_t) plane in Fig. 1. The label $\text{ALL}^{\text{-CDF}}_{\text{-ALR}}$ denotes a fit to all electroweak data except the SLD measurement of A_{LR} and the CDF kinematic fit value of m_t . The minimum value of χ^2 in this case is $\chi^2_{\text{min}} = 6.3$ at $M_H = 70$ GeV, $m_t = 150$ GeV, and the $\Delta\chi^2 = 1$ contour [which gives the 1σ ranges of m_t and M_H shown in Eq. (1)] is indicated. Also shown in the figure is the $\Delta\chi^2 = 1$ band corresponding to the SLD measurement of A_{LR} alone. As is well known, it corresponds to a much larger value of m_t for any given value of M_H , with the central value of m_t decreasing with M_H . If we combine the A_{LR} measurement with the rest of the precision electroweak data, we obtain a best fit with $\chi^2_{\text{min}} = 14.3$ at $M_H = 35$ GeV, $m_t = 153$ GeV, and the $\Delta\chi^2 = 1$ contour indicated in Fig. 1 by $\text{ALL}^{\text{-CDF}}_{\text{-ALR}}$, which results in the 1σ ranges of m_t and M_H also shown in Eq. (1). We consider that this equation represents the most complete theoretical prediction of m_t available for confrontation with the CDF measurement, as indicated by the horizontal band in Fig. 1. *It is clear that theory and experiments agree comfortably within their stated errors, and we regard this as a major success of the Standard Model at the quantum level.*

The LEP electroweak working group quotes somewhat larger values of m_t [17], essentially for three reasons. Their treatment of the available low-energy data is less complete than ours, they assume a reference central value of $M_H = 300$ GeV in the fixed interval (60, 1000) GeV, and they leave $\alpha_s(M_Z)|_{\overline{\text{MS}}}$ unconstrained. In our analysis, the low-energy data tend to pull the central value of m_t downwards, as documented previously [5]. Also, we prefer to work with M_H free, which also tends to pull m_t down, since the data prefer a low value of M_H and there is a well-known positive correlation between m_t and M_H reflected in the tilts of the $\Delta\chi^2 = 1$ contours in Fig. 1. As for the value of $\alpha_s(M_Z)|_{\overline{\text{MS}}}$, we

find that the preferred values of M_H and m_t in the global analysis of present data increase slightly with it.²

The contributions of different combinations of data to the total χ^2 as a function of M_H are shown in Fig. 2 for m_t fixed at 165 GeV. We see that the global χ^2 function now has a regular form, when plotted on a logarithmic scale for M_H , and we believe that the preference for relatively small values of M_H should be taken seriously. The χ^2 associated with the SLD measurement of A_{LR} (not included in any of the other curves) is shown separately as a dashed line in Fig. 2: we see that it tends to pull the preferred value of M_H downwards for fixed m_t , as also seen in Fig. 1 and the values reported in Eq. (1).

We now combine the precision electroweak data with the value of m_t estimated by CDF on the basis of their kinematic reconstruction: $m_t = 174 \pm 10(\text{stat.})^{+12}_{-11}(\text{syst.})$ GeV, which we interpret as $m_t = 174 \pm 16$ GeV. Excluding the SLD measurement of A_{LR} we find a best fit with $\chi^2_{\text{min}} = 7.3$ at $m_t = 164$ GeV, $M_H = 140$ GeV, and the $\Delta\chi^2 = 1, 4$ contours indicated by $\text{ALL}^{\text{-CDF}}_{\text{-ALR}}$ in Fig. 1. The small difference in χ^2 between this and the $\text{ALL}^{\text{-CDF}}_{\text{-ALR}}$ case confirms the consistency of the CDF evidence with the precision electroweak prediction. Also shown in Fig. 1 is the $\Delta\chi^2 = 1$ contour for a fit called $\text{ALL}^{\text{+CDF}}_{\text{+ALR}}$ that includes both A_{LR} and the CDF measurement: in this case $\chi^2_{\text{min}} = 15.3$ at $M_H = 50$ GeV, $m_t = 163$ GeV. We see again that adding the A_{LR} measurement pulls M_H down, whilst the range of m_t is now more stable due the CDF direct measurement.

The kinematic values of m_t are not the only relevant data published by CDF: they also quote a cross-section for $\bar{t}t$ production. As can be seen in the CDF paper [1], theoretical calculations of the $\bar{t}t$ cross section correspond to their measured value best for $m_t \simeq 140$ GeV. The combination of the cross-section data with the kinematic information would best be done by the experimentalists themselves. Nevertheless, we have done this as an exercise to obtain an indication what the most probable value might be: we find $m_t = 156 \pm 11$ GeV, with a reasonable confidence level for the combined fit, namely 12%.

The D0 collaboration report no evidence so far for the top quark, but this is not incompatible with the evidence published by CDF. The latter could have been lucky in observing an up-fluctuation in the expected number of events, in which case their cross-section estimate would be systematically high, and the value of m_t extracted above from a combined fit to their data would be biased towards a low value. This problem can

²However, if we analyze the LEP data in isolation, assuming $M_H = 300$ GeV and $\alpha_s(M_Z)|_{\overline{\text{MS}}} = 0.125 \pm 0.007$ like the LEP electroweak working group, we find $m_t = 171 \pm 15$ GeV, which differs insignificantly from the range they quote [17].

in principle be overcome by combining the CDF cross-section measurement with that reported by D0 [18], which is not by itself significantly non-zero. This combined estimate of the $t\bar{t}$ cross section can be further combined with the CDF kinematic value to obtain $m_t = 167 \pm 12$ GeV, with an overall confidence level of 9%. This is large enough to say that there is no significant discrepancy between all the CDF and D0 data. Combining this estimate of m_t with the precision electroweak data, we find the ranges of m_t and M_H shown in Eq. (3). These estimates contain in principle the most complete set of available information, but we consider them somewhat provisional, pending a combined fit to their data on m_t by the CDF and D0 collaborations themselves.

In the last part of this paper, we confront the precision electroweak data and the CDF kinematic value of m_t with the MSSM. We start by considering a case where the sparticle masses are heavy ($\mu = m_0 = m_{\tilde{g}} = 1$ TeV, in standard notation [10]) and the only light MSSM particles are the Higgs bosons (h , H , A and $H^\pm$, again in standard notation). We take m_A and $\tan\beta$ as the two independent parameters of the MSSM Higgs sector, and include the one [24] and leading two-loop [25] m_t -dependent radiative corrections to MSSM Higgs boson masses. In the limit of large $m_{H,A,H^\pm}$ and $\tan\beta$, the only light Higgs boson is the lighter neutral scalar h , and its couplings are the same as those of the single Higgs boson in the Standard Model.

Figure 3 compares χ^2 for ALL+CDF fits to the Standard Model and the MSSM as functions of the Standard Model Higgs mass M_H (dashed line) and the lighter scalar neutral MSSM Higgs mass m_h (solid line), plotted on the same scale, for three representative values of m_t and $\tan\beta = 4$. We see that the Standard Model and MSSM χ^2 values are quite similar over the allowed range of m_h , which is bounded below by the requirement $m_A > 0$, and above by the limit of large m_A . We note that when m_t is large (e.g., the $m_t = 190$ curve in Fig. 3), the preferred value of M_H in the Standard Model is considerably beyond the allowed range of m_h , implying that the MSSM scenario is worse than the Standard Model one ($\Delta\chi^2 > 4$, i.e., $> 2\sigma$ in the $m_t = 190$ GeV case). However, the MSSM fit is not significantly worse for $m_t \lesssim 170$ GeV.

Figure 4 shows $\Delta\chi^2 = 1$ contours in the (m_h, m_t) plane for ALL+CDF fits. Also shown are the theoretical upper and lower limits on m_h for $\tan\beta = 2, 16$. For each case, the point with minimum χ^2 lies within the allowed range of m_h for $\tan\beta = 16$, and is within one unit of corresponding $\chi^2_{\min}$ in the Standard Model case. The $\Delta\chi^2 = 1$ contours are always truncated at large values of m_h by the theoretical bound, and also at small values of m_h for the analyses including the SLD measurement of A_{LR} . The upper 1σ limit

on m_t is always slightly lower than in the Standard Model, since the positive correlation effect with the Higgs mass is now bounded. Again we see that a large value of m_t would disfavour the MSSM Higgs sector. This is not the case at present, and we can conclude that the MSSM is as successful as the Standard Model in predicting the measured value of m_t , at least in the heavy-sparticle limit.

We have also made MSSM analyses using smaller values of the sparticle mass parameters μ , m_0 and $m_{\tilde{g}}$, but report just one study here. The CDF collaboration have published lower limits on squarks and gluinos [26], which can be expressed as exclusion plots in the $(m_0, m_{\tilde{g}})$ plane if one assumes the standard unified mass relations in the MSSM [10]. The mass limits depend on the values assumed for the other MSSM parameters, and the CDF collaboration exhibited the exclusion contour for the particular choice $\mu = -250$ GeV, $m_A = 500$ GeV and $\tan\beta = 2$. We have made a MSSM analysis of the precision electroweak data for the same choices of μ , m_A and $\tan\beta$, also assuming the standard unified MSSM mass relations. We exhibit in Fig. 5 the $\Delta\chi^2 = 2.7$ contour (90% C.L. on each variable separately) in the $(m_0, m_{\tilde{g}})$ plane for the ALL+CDF fit at a fixed value $m_t = 165$ GeV, together with the published CDF direct limits on squark and gluinos and limits from the non-observation of charginos and sleptons at LEP. We see that the limits from precision electroweak data are tighter than those from LEP and competitive with those from CDF, becoming even stronger for small m_0 . The suggestion [27] that there might be a light chargino just above the present LEP direct search limit is essentially excluded by the CDF search (at least in this scenario), as well as being disfavoured by the latest precision LEP data (in particular on Γ_Z) and the measurement of m_t .

We have discussed previously the incorporation of the supersymmetric GUT constraint on $\sin^2\theta_W(M_Z)|_{\overline{\text{MS}}}$ in a global analysis of the electroweak data [28], and the possibility that it could provide upper bounds on sparticle mass parameters. As was previously mentioned, it is not possible to establish any model-independent upper limits that are of immediate phenomenological relevance, and we do not re-discuss this point in the light of the latest data.

The general picture that emerges from our analysis is one of striking consistency between the m_t predictions of the Standard Model and the MSSM with the top quark mass measured by CDF. We consider this agreement a tremendous theoretical success for the Standard Model, since it relies on calculations at and beyond the one-loop level, involving the whole paraphernalia of renormalization in a spontaneously-broken gauge theory. We also consider it a tremendous tribute to the persistence and accuracy of electroweak

experimentalists, particularly at LEP, that the error in the prediction of m_t is comparable with the CDF measurement error. The consistency between the indirect prediction and the direct measurement by the CDF collaboration can be regarded as cementing the interpretation of the latter's events as $t\bar{t}$ production and decay. The observation of the top quark already sharpens somewhat the prediction of M_H from precision electroweak experiments interpreted within the Standard Model. We can expect this trend to develop in the future, as the error in the direct measurement of m_t is decreased and precision electroweak data errors (particularly on A_{LR} and M_W) are also reduced. The present apparent discrepancy between the SLD measurement of A_{LR} and the rest of the precision electroweak data is disturbing, but does not affect the global consistency of those data with the measured value of m_t and indications of a relatively light Higgs boson, and we expect this apparent discrepancy to disappear in due time. One could wish that precision electroweak data would eventually discriminate between the Standard Model and the MSSM. This could happen if the data came to indicate a large value of M_H , but this is not the case at present, since the data still prefer a mass around 100 GeV as predicted by the MSSM. We regard this as circumstantial support for the supersymmetric worldview, but can only wait to see whether it is confirmed by future developments.

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Figure Captions

Fig. 1 — Contours of $\Delta\chi^2 = 1$ in the (M_H, m_t) plane for the Standard Model analysis of all electroweak data (ALL), including (+) or not (–) the SLD measurement of A_{LR} (ALR) and the CDF kinematic fit to m_t (CDF). The $\Delta\chi^2 = 1$ bands allowed by CDF and ALR alone are shown separately. For the ALL+CDF fit, which combines the LEP, CDF and low-energy data, the $\Delta\chi^2 = 4$ (2σ) contour is also shown.

Fig. 2 — Curves of χ^2 as a function of M_H at $m_t = 165$ GeV, for different combinations of precision electroweak data: vector boson masses ($M_W + M_Z$), low-energy data (LE), asymmetries at the Z^0 peak (ASY), Z^0 lineshape and partial-width data (WID), all LEP data (LEP), all high-energy data (HE), all data (ALL). The χ^2 contribution of the SLD measurement of A_{LR} (not included in ASY, HE, ALL) is shown separately (dashed line), and is seen to prefer unphysically low values of M_H .

Fig. 3 — Curves of χ^2 as function of the (lightest) Higgs boson mass in the Standard Model (dashed line) and the MSSM (solid line) at $m_t = 150, 170, 190$ GeV, using ALL+CDF data. In the MSSM case we choose $\tan\beta = 4$, $\mu = m_j = m_0 = 1$ TeV. Notice that the dashed and solid curves are very close and finally merge when m_h reaches its theoretical upper limit.

Fig. 4 — Contours of $\Delta\chi^2 = 1$ in the (m_h, m_t) plane for the MSSM analysis of all electroweak data (ALL), including (+) or not (–) the SLD measurement of A_{LR} (ALR) and the CDF kinematic fit to m_t (CDF). All sfermion and gaugino masses are set to large values by choosing $\mu = m_j = m_0 = 1$ TeV. Also shown are the theoretical lower and upper bounds on m_h for $\tan\beta = 2$ and 16, corresponding to $m_h = 0, \infty$. Actually each curve is slightly dependent on $\tan\beta$ within the allowed range; the difference is however negligible for our purposes, and a smoothed average is shown.

Fig. 5 — Exclusion plot in the (m_0, m_j) plane for $m_t = 165$ GeV, $\mu = -250$ GeV, $m_h = 500$ GeV, $\tan\beta = 2$. The solid curve labelled "MSSM R.C." encloses the region excluded by our ALL+CDF fit (with MSSM radiative corrections) at $\Delta\chi^2 = 2.7$ (90% C.L. on each variable separately). Also shown are the limits on slepton and chargino masses from LEP, and the exclusion contours from the negative results of CDF searches for gluinos and squarks (CDF solid line: with cascade decays; CDF dashed line: no cascade decays; the cusp corresponds to the case $m_j = m_{\tilde{g}}$; see Ref. [26]). Notice that the region just above the chargino threshold $M_Z/2$ is here excluded both by CDF and the MSSM R.C. analysis (assuming the standard mass relations in the MSSM).

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5