New bounds on m_t and first bounds on M_H from precision electroweak data

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Abstract

We present new results from a global analysis of all the electroweak data including precision measurements of the Z^0 mass and decays from LEP. Data from both low-energy and high-energy experiments indicate independently that the top quark mass $m_t \sim 100$ to 160 GeV. When combined they give

$$m_t = 127^{+24}_{-30} \text{ GeV},$$

for the Higgs mass $M_H = M_Z$. For the first time, the data also give non-trivial bounds on M_H : independently of m_t

$$1.8 \text{ GeV} < M_H < 6 \text{ TeV} \quad (68\% \text{ C.L.}),$$

with the preferred value of M_H being below M_Z . Furthermore, if the top quark were found below the above central value, the data would provide a stronger upper bound:

$$\ln \left(\frac{M_H}{M_Z} \right) < 3.97 - 8.90 \left(\frac{m_t}{M_Z} \right) + 5.56 \left(\frac{m_t}{M_Z} \right)^2 \quad (68\% \text{ C.L.}),$$

which gives $M_H < 600 \text{ GeV}$ for $m_t \leq 120 \text{ GeV}$.

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therefore appropriate to continue to analyze these data within the context of the minimal Standard Model. These Z^0 decay data already give a precision in $\sin^2\theta_w$ approaching that obtained from previous data, and larger statistics and better control of systematic errors should soon enable them to surpass the precision of low-energy data.

We give in this paper the results of the first global fit to all the electroweak data including those on Z^0 decay widths as well as measurements of M_Z and low-energy data. We include the Z^0 decay (ZD) data as a "fifth sector" of electroweak data that we analyze together with the previous 4 sectors, that comprised $\nu - q$ interactions, $\nu - e$ interactions, $e - q$ interactions and vector boson masses (VBM).

We discuss the ranges of m_t consistent with various subsets of the data, and find that both the low-energy ($\nu - q$, $\nu - e$ and $e - q$) and high-energy (VBM and ZD) sectors independently indicate $m_t \sim 100$ to 160 GeV. Combining all the data, we find that

$$m_t = 127^{+24}_{-30} \text{ GeV}, \quad (1)$$

for $M_H = M_Z$. For the first time, the precision electroweak data also bound M_H independently of m_t ,

$$1.8 \text{ GeV} < M_H < 6 \text{ TeV} \quad (68\% \text{ C.L.}), \quad (2)$$

with the preferred value of M_H being below M_Z . The above bound can be strengthened by measuring m_t :

$$\ln \left(\frac{M_H}{M_Z} \right) < 3.97 - 8.90 \left(\frac{m_t}{M_Z} \right) + 5.56 \left(\frac{m_t}{M_Z} \right)^2 \quad (68\% \text{ C.L.}), \quad (3)$$

which gives $M_H < 600$ GeV for $m_t = 120$ GeV. The most important contribution to the bounds on M_H comes from the consistency of the new Z^0 decay data with the other sectors.

The approach we follow is the same described in the previous papers [3], based on the comparison of the behaviour of $\sin^2\theta_w$ as a function of m_t extracted from each sector. The different behaviours, first illustrated in [3], constrain m_t (and, as we will see, now also M_H), within well-defined ranges of values. One new point is however worth mentioning. Since the data become more and more precise, we have further

There are several aspects to the interest and importance of precision electroweak measurements. These include the opportunity they offer to check the basic viability of the Standard Model, the possibility of obtaining predictions from radiative corrections for the masses of particles expected in the Standard Model but not yet seen, namely the top quark and the Higgs boson, and the opportunity to look for physics beyond the Standard Model, such as Z' , supersymmetry, or Grand Unified Theories (GUTs). A Z' could give observable deviations from the Standard Model Z^0 couplings at the tree level, supersymmetric particles could show up indirectly via radiative corrections, and GUTs make specific predictions for the Standard Model couplings, in particular $\sin^2\theta_w$, that can be confirmed or refuted.

The story of the analysis of precision electroweak data has contained two phases so far. The first phase comprised several sets of low-energy data, of which the most precise were those from deep-inelastic $\nu - N$ scattering, and the first, relatively imprecise, measurements of M_W and M_Z from $p\bar{p}$ colliders [1] [2]. Already, the comparison between these low-energy data and the embryonic high-energy measurements indicated that the top quark mass could not be very high: $m_t < 171$ (207) GeV at the 68.3 (90)% confidence level [3]. The second phase saw the appearance of the first precision measurements of M_Z from the SLC and LEP. The effect of these was to give a very tight correlation between the allowed value of $\sin^2\theta_w$ and m_t . When combined with the low-energy data and collider measurements of M_W/M_Z , the precision M_Z measurements greatly restricted the allowed range of the top quark mass: the first SLC measurement led to $m_t = 132^{+31}_{-37}$ GeV [4], and the precise measurements of M_Z during the 1989 run of LEP further improved the estimate to $m_t = 135^{+27}_{-31}$ GeV [5].

Now a third phase in the precision electroweak story is unfolding, with the advent of precision measurements of Z^0 decay properties, including the total Z^0 width, several partial widths, and the forward-backward asymmetries for Z^0 decays into leptons and b quarks. *Prima facie*, the new data are in perfect agreement with the Standard Model and predictions based on previous data, with no evidence for a Z' , for example. It is

refined our approach by estimating the radiative corrections for each pair of values of m_t and M_H in such a way as to have the best consistency with data. So, for assigned m_t and M_H we have derived $\sin^2\theta_w$, defined according the on-shell scheme proposed by Sirlin [6], through an iterative procedure from the implicit equation

$$\sin^2\theta_w \cos^2\theta_w = \frac{1}{M_Z^2} \frac{\pi\alpha}{\sqrt{2}G_\mu} \frac{1}{1 - \Delta r(\sin^2\theta_w, M_Z, m_t, M_H)}, \quad (4)$$

which defines, as is well-known [6], the radiative corrections to the vector boson masses within the Standard Model.

Before addressing the "beef" of this paper in the high-energy (HE) sector, we first update the low-energy (LE) data, which involve $\nu-q$, $\nu-e$ and $e-q$ interactions. There has been no significant change in the $\nu-q$ sector, which is dominated by deep-inelastic νN and $\bar{\nu}N$ total cross-section data. Their $1-\sigma$ contour for $\sin^2\theta_w$ as a function of m_t is shown in Fig. 1 for $M_H = M_Z$ and $m_c = 1.45$ GeV. The minimum of χ^2 for these data alone is at $m_t = 143$ GeV, with $m_t < 257$ GeV at the 68.3% confidence level. As we have discussed previously [4], $m_c = 1.45$ GeV is the central value preferred by the νN and $\bar{\nu}N$ total cross-section data themselves, and corresponds to other independent estimates of m_c . Recently, a comprehensive analysis of dimuon data in νN and $\bar{\nu}N$ collisions has been made [7], which confirms the so-called "slow rescaling" scheme of the threshold effect in the charm production and gives $m_c = 1.34 \pm 0.21_{-0.04}^{+0.25}$ GeV, consistent with our choice of m_c . An uncertainty of 0.3 GeV applied to the value of m_c in the analysis of the νN and $\bar{\nu}N$ data may be approximately modelled by expanding the error in the determination of the squared chiral couplings of a factor 1.5 [2]. We will comment later on the implications of making this extra allowance.

There have been two new developments in the $\nu-e$ sector, namely a new determination of $\sin^2\theta_w$ from the ratio $\sigma(\bar{\nu}_\mu e)/\sigma(\nu_\mu e)$ by the CHARM II Collaboration [8], $\sin^2\theta_w = 0.240 \pm 0.012$ from a tree level fit, and a refinement of the measurement of the $\nu_e e$ cross-section from the LAMPF experiment E225 [9], $\sigma(\nu_e e) = [9.9 \pm 1.5(\text{stat}) \pm 1.0(\text{syst})] 10^{-42} \text{ cm}^2 \cdot E_\nu (\text{GeV})$. Both these new improvements have been included in the analysis of the $\nu-e$ sector, together with the set of data already considered in [4].

The most important new development in the $e-q$ sector has been a new theoretical calculation [10] of the atomic matrix elements controlling the parity-violating effect measured in Cesium: the new estimates of $\mathcal{E}_{\text{PNC}}$ and β (see [10] for details)

$$\begin{cases} \mathcal{E}_{\text{PNC}} = -(0.900 \pm 0.006) \times 10^{-11} (-Q_w/N) i|e|a_0 \\ \beta_A = (27.06 \pm 0.20)\omega_0^2 \end{cases} \quad (5)$$

are in good agreement with the previous estimates [11], and reduce the theoretical uncertainty on $\sin^2\theta_w$ deduced from the $e-q$ sector to the order of 1.5%. Clearly, a significant reduction in the experimental error (the best measurement at present is that of the Boulder group [12], with $\Delta\sin^2\theta_w|_{\text{exp}} \simeq 0.007$) would be well-matched to the theoretical precision, but already atomic physics parity-violation is the most precise determination of $\sin^2\theta_w$ in the $e-q$ sector. However, the present $e-q$ data by themselves give only $m_t < 303$ GeV at the 68.3% confidence level, and no lower limit.

In Fig. 1 we have plotted also the $1-\sigma$ contour of $\sin^2\theta_w$ as a function of m_t for $M_H = M_Z$ for the $\nu-e$ and $e-q$ sectors combined together. We obtain a rather broad band, because the experimental uncertainties are still large. However, the divergence of the m_t -dependences at large m_t of the $\nu-q$ sector on the one hand and of the $\nu-e$ and $e-q$ sectors on the other, which is visible in Fig. 1, constrain the allowed region to a restricted zone. The low-energy data by themselves give then an upper bound on m_t , but not a lower bound:

$$\text{LE:} \quad m_t = 106 \quad +61 \quad -\dots \quad \text{GeV} \quad (6)$$

for $M_H = M_Z$.

As already mentioned, the main novelty in this global analysis of electroweak data, compared with those published previously, is however the inclusion of precision Z^0 decay (ZD) data, so we describe in some detail our procedure for treating these results and incorporating them in our global fit. Measurements have been reported of the total Z^0 decay width Γ_Z , its hadronic partial width Γ_h , its various leptonic partial widths $\Gamma_{e,\mu,\tau}$, its invisible partial width Γ_{inv} , and certain forward-backward asymmetries. Since all measurements are consistent with the Standard Model, we use it to parametrize all

these data. This means in particular that we assume lepton universality and work only with $\Gamma_e = \Gamma_\mu = \Gamma_\tau = \Gamma_\nu$, and also that we assume that $\Gamma_{\text{inv}} = 3\Gamma_\nu$ with no allowance for other invisible Z^0 decay modes. Measurements of forward-backward asymmetries on the Z^0 peak do not yet have equivalent precision, e.g. in determining $\sin^2\theta_w$, to the decay width measurements. Therefore we do not include them in this analysis, but plan to include them in a more complete analysis of all the 1990 LEP data. After the above simplifications, we are left with 3 different pieces of information, namely Γ_Z , Γ_h and Γ_t with $\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_h - 3\Gamma_t$.

Rather than use straightforwardly the quoted values of these quantities, we have chosen to work with the quoted values of 3 equivalent quantities that are more directly related to the experimental data, and whose correlations are simpler to discuss. We work with the total width Γ_Z , which is determined by the overall line-shape, the tree-level peak hadronic cross-section

$$\sigma_{\text{peak}}^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_t}{\Gamma_Z} \frac{\Gamma_h}{\Gamma_Z}, \quad (7)$$

evaluated after removal of electromagnetic radiative corrections, and the ratio

$$R \equiv \frac{\Gamma_h}{\Gamma_t}, \quad (8)$$

which is largely independent of systematic errors in the luminosity measurements.

The relevant formulae for Γ_Z , Γ_h and Γ_t are well-known both at the tree level and to the one-loop level, so we do not reproduce them here, but limit ourselves to two comments. The first concerns the $Z^0 \rightarrow b\bar{b}$ decay width, which contains additional top quark exchange diagrams among the vertex corrections that are absent or Cabibbo-Kobayashi-Maskawa-suppressed for the other $Z^0 \rightarrow q\bar{q}$ decays. All these effects, as estimated for example in [13], have been included in our calculations[†], and we have verified the numerical results tabulated in [14]. The second comment concerns QCD corrections to Γ_h and Γ_t . The QCD corrections to Γ_h have been calculated to order

[†] Ref. [13] contains however two misprints. There should be a factor $\frac{1}{4}$ instead of $\frac{1}{2}$ multiplying the first term in the expression for $C_2^0(s, M, M')$ in eq. (5.9), and a - sign has been omitted in the expression of x_1 in eq. (5.12).

$(\alpha_s/\pi)^3$, but only the next-to-leading contributions to the other QCD observables, such as jet cross-sections and energy-energy correlations, that are used in independent determinations of $\alpha_s(M_Z)$. For this reason, and because the published coefficient of $(\alpha_s/\pi)^3$ in Γ_h apparently requires some correction, we only use the calculations of Γ_h to order $(\alpha_s/\pi)^2$. We take from a recent review [15] of data on hadronic final states in Z^0 decay $\alpha_s(M_Z) = 0.115 \pm 0.016$, and estimate the uncertainty induced in our analysis by the quoted error on α_s . Since this determination is independent of the width information we use to discuss $\sin^2\theta_w$, m_t and M_H , we treat this error as uncorrelated with the others.

Table I. Data set from the four LEP experiments. Data are preliminary, and are as presented at the Neutrino 90 Conference [16]. For previous published data see [17]. In the last row the average of the four experiments is reported, first with the averaged statistical error, then adding quadratically also the common systematic uncertainty.

experiment	M_Z (GeV)	Γ_Z (MeV)	σ_{peak}^0 (nb)	$R \equiv \Gamma_h/\Gamma_t$
ALEPH	91.194 ± 0.016	2498 ± 31	41.36 ± 0.66	20.77 ± 0.39
DELPHI	91.182 ± 0.021	2495 ± 40	41.7 ± 1.2	20.8 ± 0.6
L3	91.148 ± 0.017	2502 ± 33	41.24 ± 0.76	20.57 ± 0.60
OPAL	91.163 ± 0.017	2497 ± 34	41.6 ± 0.8	$21.72^{+0.71}_{-0.65}$
Average	91.172 ± 0.009	2498 ± 0.017	41.63 ± 0.40	20.89 ± 0.27
	91.172 ± 0.031	2498 ± 0.020	41.63 ± 0.60	20.89 ± 0.27

The LEP data set we use as input for our global electroweak fit is shown in Table

I. These data were presented at the Neutrino 90 Conference at CERN [16]. Some of the data are derived from measurements taken during 1989 only, whereas others also include some 1990 events. On the basis of Table I, we use

$$\Gamma_Z = 2498 \pm 20 \text{ MeV}, \quad \sigma_{\text{peak}}^0 = 41.63 \pm 0.60 \text{ nb}, \quad R = 20.89 \pm 0.27, \quad (9)$$

where the errors contain both statistical errors (averaged over the four LEP experiments) and systematic uncertainties (assumed common to all of them). In order to use these data correctly, it is also necessary to know the correlation matrix for the errors, which is not generally published by all the experiments. However, on the basis of an analysis by the ALEPH Collaboration we include a non-zero correlation only between the two first variables, Γ_Z and σ_{peak}^0 , which appear rather strongly correlated, adopting a correlation coefficient -0.46 .

We obtain from these Z^0 decay data the $1 - \sigma$ contour for $\sin^2 \vartheta_w$ as a function of m_t shown in Fig. 2 for $M_H = M_Z$. The χ^2 distribution for these data alone is minimized when $m_t = 264 \text{ GeV}$, and we find $m_t < 354 (377) \text{ GeV}$ at the $68.3 (90)\%$ confidence level, but these data alone give no significant lower limit on m_t . However, these data do give significant information when compared with the data from other electroweak sectors, as we will discuss.

Finally, we turn to measurements of the vector boson masses (VBM). Here the most dramatic improvement during the past few months has been that in the determination of M_Z :

$$M_Z = 91.172 \pm 0.009 (\text{stat}) \pm 0.030 (\text{syst}) \text{ GeV}, \quad (10)$$

where the latter is the overall scale error in the LEP energy calibration. For any fixed values of m_t and M_H , this measurement gives a determination of $\sin^2 \vartheta_w$ that is an order of magnitude more precise than any other currently available. This narrow band of allowed values of $\sin^2 \vartheta_w$, shown in Fig. 2 for $M_H = M_Z$, is truncated by the available measurements of the ratio M_W/M_Z from $p\bar{p}$ colliders. The latest values of M_W/M_Z that we use for our fit are those from UA2 and CDF reported at the Neutrino 90 Conference [18]:

$$\begin{aligned} (M_W/M_Z)_{\text{CDF}} &= 0.8775 \pm 0.0047 (\text{stat}) \pm 0.0021 (\text{syst}) \\ (M_W/M_Z)_{\text{UA2}} &= 0.8831 \pm 0.0048 (\text{stat}) \pm 0.0026 (\text{syst}). \end{aligned} \quad (11)$$

The $1 - \sigma$ error on $\sin^2 \vartheta_w$ obtained averaging the two measurements (11) is also shown in Fig. 2. It is evident that the VBM sector, which combines the impressive precision in the measurement of M_Z with the estimate of the ratio M_W/M_Z from $p\bar{p}$ colliders, by itself gives already an interesting limit on m_t .

$$\text{VBM:} \quad m_t = 142^{+44}_{-55} \text{ GeV}, \quad (12)$$

with $70 \text{ GeV} < m_t < 205 \text{ GeV}$ at the 90% confidence level. This indication of a heavy top quark confirms on the basis of the VBM data alone a conclusion that was drawn last year on the basis of a combination of low- and high-energy data [4]. We will now see how this conclusion can be sharpened by including the Z^0 decay as well as the updated low-energy data discussed above.

Unfortunately, as already noted in [19], the m_t -dependence of the ZD sector is rather similar to that of the VBM sector, and the data are still clearly less precise. This limits the information about m_t which can be extracted by combining the two. Adding in the ZD data is however significant: it reduces somewhat the range of m_t to

$$\text{HE:} \quad m_t = 146^{+39}_{-47} \text{ GeV}. \quad (13)$$

whereas the information about m_t which can be extracted from the high-energy experiments excluding the contribution of the estimate of the ratio M_W/M_Z , i.e. from the results of LEP alone, is not yet so precise:

$$\text{LEP:} \quad m_t = 162^{+77}_{-111} \text{ GeV}. \quad (14)$$

for $M_H = M_Z$.

In Fig. 3, in order to make clear the relative relevance of the different sectors, we show the χ^2 -distributions as functions of m_t for various combinations of electroweak sectors. The line labelled ZD is that for the Z^0 decay sector alone. As mentioned earlier, it does not exhibit a strong dependence on m_t . The same is also true of the $\nu - e$ and

$e - q$ sectors, which are not shown. The $\nu - q$ sector has more m_t -dependence, but the reason for the sharp rise in the χ^2 -distribution for the combined low-energy (LE) sectors in Fig. 3 is the divergence of the m_t -dependences at large m_t already noted. A lower bound was first provided by the vector boson mass (VBM) measurements, whose χ^2 -distribution is also shown in Fig. 3, giving the range of m_t quoted in eq. (12). Also shown is the χ^2 -distribution for all high-energy data combined, i.e. the VBM and ZD sectors.

Finally, also in Fig. 3 we show the χ^2 -distribution for all the data combined, which give the best values for both m_t and $\sin^2 \theta_w$. For $M_H = M_Z$

$$\text{All } |M_H = M_Z : \quad \begin{cases} m_t = 127 & +24 & -30 & \text{GeV} \\ \sin^2 \theta_w = 0.2273 & +0.0033 & -0.0031 \end{cases} \quad (15)$$

The corresponding range for m_t if the error bars for the $\nu - q$ sector are inflated by a factor 1.5 to mimic the possible uncertainty in m_c is

$$(\nu - q)_{\text{error} \times 1.5} : \quad m_t = 133 & +29 & -36 & \text{GeV} \quad (16)$$

It is clear from the above discussion that the electroweak data have a high degree of self-consistency.

We now go on to discuss the sensitivity of the present electroweak data to M_H . Fig. 4 shows the χ^2 -distributions for different choices of M_H between 5 GeV and 1 TeV. We see that the optimum value of m_t increases monotonically from 122 GeV to 147 GeV as M_H is increased from the present experimental limit of ~ 40 GeV to the upper theoretical expectation of ~ 1 TeV. We also see that the minimum value of χ^2 increases significantly when M_H is either very small or very large. Taking the envelope of all the curves we find:

$$\text{all } M_H : \quad m_t = 122 & +41 & -32 & \text{GeV} \quad (17)$$

† At present the best experimental limit is set by ALEPH with a 95 % C.L. lower limit of 41.6 GeV [20]. For the previous limits given by the four collaborations see [21].

as the global range of m_t for all allowed values of M_H .

There is another implication concerning M_H to which we would like to draw the reader's attention. If m_t were measured directly, e.g. at the FNAL $p\bar{p}$ collider, the precision electroweak data could already give an interesting upper bound on M_H . This can be seen explicitly in Fig. 5, where we show the χ^2 -distributions as functions of M_H for various different choices of m_t . For example, if $m_t = 110$ GeV, then $M_H < 340$ GeV at the 68.3 % confidence level. For 90 GeV $< m_t < 130$ GeV this upper limit can be parametrized as in eq. (3), giving, for example, $M_H < 225, 340, 600$ GeV for $m_t = 100, 110, 120$ GeV.

The coupled information on the allowed values of m_t and M_H is expressed via the $\Delta\chi^2 = 1$ contour shown in Fig. 6. We see from this figure that the precision electroweak data already give an indirect lower bound on M_H from radiative corrections:

$$\text{all } m_t : \quad M_H > 1.8 \text{ GeV} \quad (68\% \text{ C.L.}) \quad (18)$$

This bound is of course modest compared with the direct LEP lower bound of ~ 40 GeV already quoted, but it is stronger than any other unimpeachable direct lower bound on M_H , and is independent of any assumption about the Higgs decay modes. Fig. 6 also indicates an upper bound on M_H , although this is in the region of heavy Higgs masses where perturbation theory breaks down:

$$\text{all } m_t : \quad M_H < 6 \text{ TeV} \quad (68\% \text{ C.L.}), \quad (19)$$

and should therefore be taken *cum grano salis*.

The origin of these bounds on M_H is mainly in the high-energy data sectors. The $\nu - q, \nu - e$ and $e - q$ sectors all have very flat χ^2 -distributions as functions of M_H . On the other hand, χ^2 for the VBM sector rises with M_H if $m_t \geq 120$ GeV, giving an upper bound on M_H but not a lower one. The χ^2 -distribution for the ZD sector by itself is more symmetric, tending to rise slightly at both large and small M_H . More significant bounds are obtained by combining the ZD data with either the low-energy sector or the VBM sector. Thus it is the consistency of the new ZD data with the other sectors that makes the dominant contributions to the global bounds (18) and (19) on M_H .

We have seen that the advent of high-precision LEP data on the Z^0 mass and decays have confirmed previous predictions, based on low-energy data and the first measurements of M_W and M_Z , that m_t probably lies in the range ~ 100 to ~ 160 GeV. The error in this estimate of m_t has now been reduced to the 20 % level, and it seems very likely that the top quark lies in the mass range accessible to searches at the Fermilab $p\bar{p}$ collider. We wish them happy hunting!

A novel result of our analysis is the first non-trivial information about the Higgs mass from electroweak radiative corrections. Our lower bound $M_H > 1.8$ GeV is weaker than the direct lower limit from LEP, but stronger than other direct searches. An interesting feature is the fact that uncovering the top quark in the lower half of our predicted range would give a significant upper bound: M_H less than about 600 GeV if m_t less than 120 GeV, of interest to prospective searches at the LHC and the SSC. In fact, the present data already prefer M_H not much heavier than the Z^0 . Many theorists do not believe that the single elementary physical Higgs boson of the Standard Model is the whole story, but our results probably suggest there will be some action at accessible energies even in a more complicated Higgs sector. We also wish Higgs searchers happy hunting!

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Fig. 1 — One-standard-deviation error bands on $\sin^2 \theta_w$ as functions of m_τ for the low-energy (LE) data. We show the ν - q sector, the ν - e and e - q sectors combined, and the region allowed by the complete set of LE data. We have assumed $m_c = 1.45$ GeV and $M_H = M_Z$.

Fig. 2 — One-standard-deviation error bands on $\sin^2 \theta_w$ as functions of m_t assuming $M_H = M_Z$ for the high-energy (HE) data. We show the bands corresponding to the LEP measurements of the Z mass (M_Z) and Z decays (ZD). The error on $\sin^2 \theta_w$ from measurements of M_W/M_Z is shown as a vertical error bar. Shown is also the region allowed by the complete set of HE data.

Fig. 3 — χ^2 distributions as functions of m_t assuming $M_H = M_Z$ for the ν - q , VBM, HE, LE and all data.

Fig. 4 — χ^2 distributions as functions of m_t for different choices of M_H . All the data are included.

Fig. 5 — χ^2 distributions as functions of M_H for different choices of m_t . All the data are included.

Fig. 6 — $\Delta\chi^2 = 1$ contour in the (M_H, m_t) plane: note the 68.3 % C.L. lower and upper limits on M_H of 1.8 GeV and 6 TeV, respectively. All the data are included.