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Constraints on Standard Model Parameters from Combined Preliminary Data of the LEP Experiments

The LEP Electroweak Working Group *

Internal Note

summarizing the combination of preliminary LEP data for the 27th International Conference on High Energy Physics, Glasgow, Scotland, 20-27 July 1994

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1 Introduction

In this note all LEP precision electroweak measurements described in [1, 2, 3] are summarized and interpreted in the framework of the Minimal Standard Model.

2 Determination of the effective Z^0 couplings for charged leptons

The partial widths of the Z^0 into leptons and the lepton forward-backward asymmetries [1], the τ polarization and the τ polarization asymmetry [2] can all be combined to determine the vector and axial vector couplings for e, μ and τ. The asymmetries determine the ratio g_{V_ℓ}/g_{A_ℓ} while the axial vector coupling squared is derived from the leptonic partial width. The corresponding results for the effective lepton couplings are given in Table 1. Figure 1 shows the 68% probability contours in the g_{A_ℓ}-g_{V_ℓ} plane. The measured ratios of the e, μ and τ couplings provide a test of universality:

$$g_{A_\mu}/g_{A_e}=1.0014 \pm 0.0021 \ , \ g_{A_\tau}/g_{A_e}=1.0034 \pm 0.0023 \ ,$$

$$g_{V_\mu}/g_{V_e}=0.83 \pm 0.16 \qquad , \ g_{V_\tau}/g_{V_e}=1.044 \pm 0.091 \ .$$

g_{V_e}	-0.0370 $\pm$ 0.0021
g_{V_μ}	-0.0308 $\pm$ 0.0051
g_{V_τ}	-0.0386 $\pm$ 0.0023
g_{A_e}	-0.50093 $\pm$ 0.00064
g_{A_μ}	-0.50164 $\pm$ 0.00096
g_{A_τ}	-0.5026 $\pm$ 0.0010
g_{V_ℓ}	-0.0366 $\pm$ 0.0013
g_{A_ℓ}	-0.50128 $\pm$ 0.00054

Table 1: Results for the leptonic vector and axial vector couplings without and with the assumption of lepton universality.

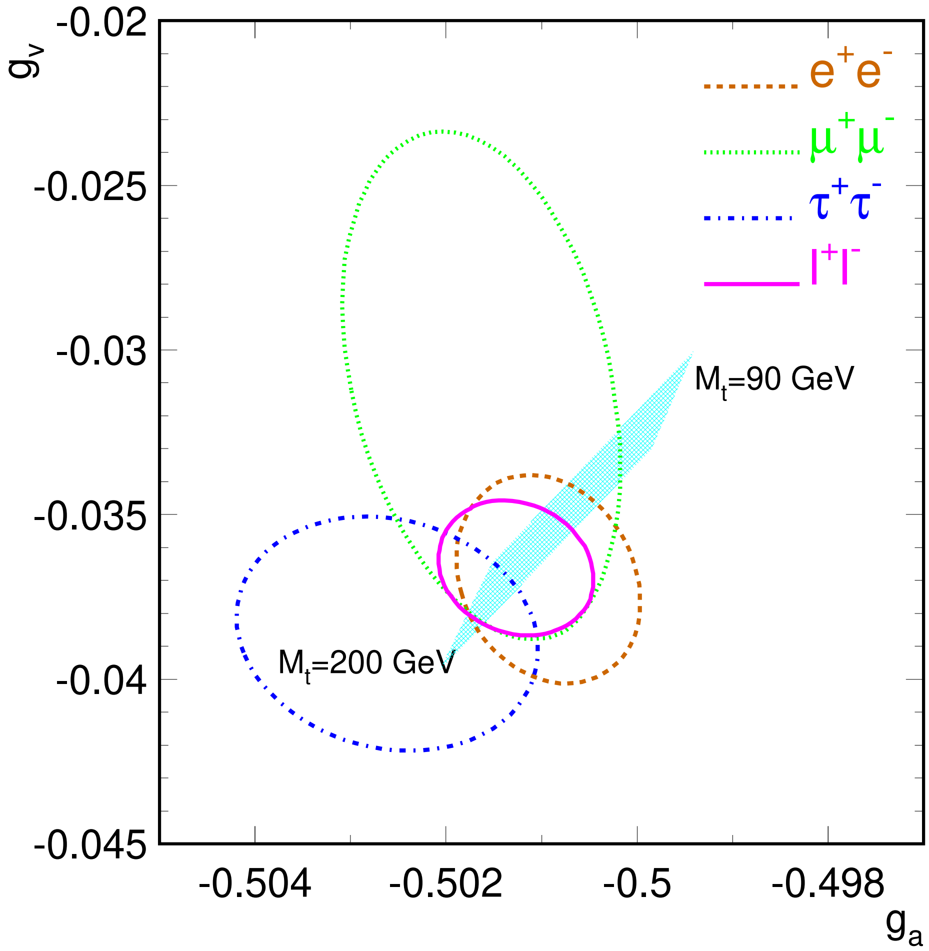

Figure 1: 68% probability contours in the g_{V_ℓ}-g_{A_ℓ} plane. The solid contour results from a fit assuming lepton universality. The shaded band represents the Standard Model prediction.

3 The Effective Electroweak Mixing Angle $\sin^2\theta_{eff}^{\rm lept}$

Table 2 shows the results of various determinations of $\sin^2\theta_{eff}^{\rm lept}$ from the data given in [1, 2, 3] and their combination . Also the comparison with the measurement of the left-right asymmetry, $A_{\rm LR}$, at SLC is given [4].

	$\sin^2\theta_{eff}^{\rm lept}$	average by group of observations	$\chi^2/(d.o.f.)$	cumulative average	$\chi^2/(d.o.f.)$
$A_{FB}^{0,\ell}$	0.2311 ± 0.0009				
$\mathcal{A}_\tau$	0.2320 ± 0.0013				
$\mathcal{A}_e$	0.2330 ± 0.0014	0.2317 ± 0.0007	1.4/2	0.2317 ± 0.0007	1.4/2
$A_{FB}^{0,b}$	0.2327 ± 0.0007				
$A_{FB}^{0,c}$	0.2310 ± 0.0021	0.2325 ± 0.0006	0.6/1	0.2321 ± 0.0005	2.8/4
$\langle Q_{FB} \rangle$	0.2320 ± 0.0016	0.2320 ± 0.0016	–	0.2321 ± 0.0004	2.8/5
$A_{\rm LR}$ (SLC)	0.2294 ± 0.0010	0.2294 ± 0.0010	–	0.2317 ± 0.0004	9.0/6

Table 2: Comparison of several determinations of $\sin^2\theta_{eff}^{\rm lept}$ from asymmetries. Averages are obtained as weighted averages assuming no correlations.

4 Standard Model Constraints

The precision electroweak measurements performed at LEP can be used to check the validity of the Standard Model and to infer valuable information about its basic parameters. Their accuracy makes them sensitive to the top quark mass, $M_{\rm t}$, and to the mass of the Higgs boson, $M_{\rm H}$, through the loop corrections. The leading top quark dependence is quadratic and allows a determination of $M_{\rm t}$. The main dependence on $M_{\rm H}$ is logarithmic and therefore, with the present data accuracy, the interpretation in terms of $M_{\rm H}$ is still a delicate subject.

The various measurements are summarized in Table 3 and presented in Figure 2 together with their Standard Model prediction as a function of $M_{\rm t}$.

The theoretical uncertainties are dominated by the uncertainty in the value of $\alpha(M_Z^2)$ due to the contribution of light quarks to the photon vacuum-polarization. An uncertainty $\delta\Delta\alpha = 0.0009$ has been propagated in the fits.

The bands in the Standard Model predictions reflect the linear sum of the expected variations of each quantity due to a change of the strong coupling constant $\alpha_s(M_Z^2) = 0.123 \pm 0.006$ [6] and $M_{\rm H}$ in the interval $60 \leq M_{\rm H}$ [GeV] ≤ 1000 for $M_{\rm Z} = 91.1888$ GeV.

	measurement	Standard Model fit	pull
a) LEP			
line-shape and lepton asymmetries:			
M_Z [GeV]	91.1888 ± 0.0044	91.1887	0.0
Γ_Z [GeV]	2.4974 ± 0.0038	2.4973	0.0
σ_h^0 [nb]	41.49 ± 0.12	41.437	0.4
R_ℓ	20.795 ± 0.040	20.786	0.2
$A_{FB}^{0,\ell}$	0.0170 ± 0.0016	0.0153	1.0
+ correlation matrix [1]			
τ polarization:			
$\mathcal{A}_\tau$	0.143 ± 0.010	0.143	0.0
$\mathcal{A}_e$	0.135 ± 0.011	0.143	-0.7
b and c quark results:			
$R_b = \Gamma_{b\overline{b}}/\Gamma_{had}$	0.2202 ± 0.0020	0.2158	2.2
$R_c = \Gamma_{c\overline{c}}/\Gamma_{had}$	0.1583 ± 0.0098	0.172	-1.4
$A_{FB}^{0,b}$	0.0967 ± 0.0038	0.1002	-0.9
$A_{FB}^{0,c}$	0.0760 ± 0.0091	0.0714	0.5
+ correlation matrix [3]			
$q\overline{q}$ charge asymmetry:			
$\sin^2\theta_{eff}^{lept}$ from $\langle Q_{FB}\rangle$	0.2320 ± 0.0016	0.2320	0.0
b) $p\overline{p}$ and νN			
M_W [GeV] (CDF, CDF prel., D0 prel., UA2; [5])	80.23 ± 0.18	80.31	-0.5
$1 - M_W^2/M_Z^2(\nu N)$	0.2256 ± 0.0047	0.2243	0.3
c) SLC			
$\sin^2\theta_{eff}^{lept}$ from $\mathcal{A}_e$	0.2294 ± 0.0010	0.2320	-2.6

Table 3: Summary of measurements included in the combined analysis of Standard Model parameters. Section a) summarizes LEP averages, section b) electroweak precision tests from hadron colliders and νN-scattering, section c) gives the result for $\sin^2\theta_{eff}^{lept}$ from the measurement of the left-right polarization asymmetry at SLC. The Standard Model fit result in column 3 and the pulls in column 4 are derived from the fit including all data (Table 4, column 4) for a fixed value of $M_H = 300$ GeV.

Table 4 shows the constraints obtained on M_t and $\alpha_s(M_Z^2)$ when fitting all the above measurements to the most up to date Standard Model calculations [7], as verified by the working group on "Precision Calculations at LEP-I" [8]. The fits have been repeated for $M_H = 60$, 300 and 1000 GeV and the difference in the fitted parameters is quoted as an uncertainty. We present the results obtained using only LEP data, as well as those obtained by including the measurements of M_W from UA2 [9], CDF [10, 11] and D0 [11], and the measurements of the neutrino neutral to charged current ratios from CDHS [12], CHARM [13] and CCFR [14]. Finally we also add the SLC result for the left-right asymmetry, A_{LR} [4]. The $\chi^2/(d.o.f.)$ for all these fits is acceptable. The value of $\alpha_s(M_{\mathrm{Z}}^2)$ resulting from these fits is in very good agreement with that obtained from event shape measurements at LEP ($\alpha_s(M_{\mathrm{Z}}^2) = 0.123 \pm 0.006$ [6]) and of similar precision. Similarly, the value of M_{t} resulting from these fits is in excellent agreement with the direct search evidence reported by CDF of $M_{\mathrm{t}} = 174 \pm 10^{+13}_{-12}$ GeV. For the first time there is therefore evidence that the bulk of non-trivial quantum effects in precision electroweak observables is indeed due to the top quark, as predicted by the Standard Model.

	LEP	LEP + Collider and ν data	LEP + Collider and ν data + A_{LR} from SLC
M_{t} (GeV)	$173^{+12}_{-13}{}^{+18}_{-20}$	$171^{+11}_{-12}{}^{+18}_{-19}$	$178^{+11}_{-11}{}^{+18}_{-19}$
$\alpha_s(M_{\mathrm{Z}}^2)$	$0.126 \pm 0.005 \ \pm 0.002$	$0.126 \pm 0.005 \ \pm 0.002$	$0.125 \pm 0.005 \ \pm 0.002$
$\chi^2/(d.o.f.)$	7.6/9	7.7/11	15/12
$\sin^2\theta_{eff}^{\mathrm{lept}}$	$0.2322 \pm 0.0004 \ ^{+0.0001}_{-0.0002}$	$0.2323 \pm 0.0003 \ ^{+0.0001}_{-0.0002}$	$0.2320 \pm 0.0003 \ ^{+0.}_{-0.0002}$
$1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2$	$0.2249 \pm 0.0013 \ ^{+0.0003}_{-0.0002}$	$0.2250 \pm 0.0013 \ ^{+0.0003}_{-0.0002}$	$0.2242 \pm 0.0012 \ ^{+0.0003}_{-0.0002}$
M_{W} (GeV)	$80.28 \pm 0.07 \ ^{+0.01}_{-0.02}$	$80.27 \pm 0.06 \ ^{+0.01}_{-0.01}$	$80.32 \pm 0.06 \ ^{+0.01}_{-0.01}$

Table 4: Results of fits to LEP and other data for M_{t} and $\alpha_s(M_{\mathrm{Z}}^2)$. No external constraint on $\alpha_s(M_{\mathrm{Z}}^2)$ has been imposed. In the third column also the combined data from the $\mathrm{p\overline{p}}$ experiments UA2 [9], CDF [10, 11] and D0 [11]: $M_{\mathrm{W}} = 80.22 \pm 0.16$ GeV and from the neutrino experiments, CDHS [12], CHARM [13] and CCFR [14]: $1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2 = 0.2256 \pm 0.0047$ are included. The fourth column gives the result when also the SLD measurement of the left-right asymmetry at SLC [4], $\sin^2\theta_{eff}^{\mathrm{lept}} = 0.2294 \pm 0.0010$, is added. The central values and the first errors quoted refer to $M_{\mathrm{H}} = 300$ GeV. The second errors correspond to the variation of the central value when varying M_{H} in the interval $60 \leq M_{\mathrm{H}}$ [GeV] ≤ 1000.

If taken at face value, R_{b} differs from the Standard Model prediction by 2.2 standard deviations (see Table 3). However it is worth remarking that there is a strong correlation (of about -40%) between the R_{b} and R_{c} measurements. In fact the discrepancy between R_{b} and its Standard Model prediction decreases to 1.9 standard deviations if the value of R_{c} is fixed to the Standard Model value $R_{\mathrm{c}} = 0.171$ (at present the R_{c} measurement is also 1.4 sigma off). In this case one in fact obtains:

$$R_{\mathrm{b}} = 0.2192 \pm 0.0018$$

Since the b partial width is a component of the total hadronic width, a possible discrepancy with respect to the Standard Model could also be revealed by R_ℓ. In Figure 4 the measured value of R_{b} is plotted versus $\sin^2\theta_{eff}^{\mathrm{lept}}$. If one assumes the Standard Model dependence on $\sin^2\theta_{eff}^{\mathrm{lept}}$ for the light quark widths and taking for $\alpha_s(M_{\mathrm{Z}}^2)$ the value 0.123 ± 0.006, R_ℓ imposes a constraint on these two variables, which is represented by the inclined band. The one sigma R_ℓ band agrees with the Standard Model prediction while the R_{b} band does not.

Figure 5 shows, for the fit in Table 4 column 4, the χ^2 value as a function of $M_{\rm t}$ for the three values of $M_{\rm H}$ considered in Table 4.

At present, the increase in χ^2 when $M_{\rm H}$ is changed between the two extreme values is about 2.0 for the LEP data alone and about 3.6 when including collider, νN and SLC data. Such a variation does not allow to derive meaningful constraints on $M_{\rm H}$. For the fit to the LEP data alone, most of the χ^2 increase can be still traced back to the contributions of $R_{\rm b}$ and R_ℓ. In the fit to all data, the trend to low Higgs mass values is further enhanced by the SLC measurement of $A_{\rm LR}$. Our conclusion of ref. [15] that the present increase in χ^2 with $M_{\rm H}$ is due to a fluctuation of the data and hence its interpretation has to be taken with care, still holds. In fact such fluctuations are not the most likely, but still perfectly plausible.

To illustrate this problem, in fig. 6a we show the χ^2 as a function of $\log_{10}(M_{\rm H})$ as observed in the data versus the theoretical expected sensitivity, i.e. the sensitivity that can be predicted given the present errors. This comparison reveals that the large sensitivy shown by the data is not supported by its expectation and hence, assuming that the Standard Model is the right description of the data, it can be traced back to fluctuations in some relevant data (such as $R_{\rm b}$ and R_ℓ, for instance). The sensitivity shown by the data is therefore not robust with respect to input data fluctuations.

If the CDF determination of $M_{\rm t}$ is used as an additional constraint in the electroweak fits, then $M_{\rm H}$ is the only free parameter left. In this case the comparison between observed and expected sensitivity (fig. 6b) shows a good agreement. The robustness of this sensitivity is such that the width of the parabola remains almost constant regardless of whether the measurements which were "causing problems" before are used in the fit or not.

Since the measurements are directly sensitive to $\log_{10}(M_{\rm H})$, fluctuations in the position of the minimum (even if small in the $\log_{10}(M_{\rm H})$ scale in comparison to the width of the χ^2 parabola) correspond to very important changes in $M_{\rm H}$. Therefore, in spite of the reliability of the present determination of $\log_{10}(M_H)$, its translation in terms of a measurement of $M_{\rm H}$ leads to conclusions which strongly depend on the chosen input data and on their fluctuations.

To conclude, the only two statements which in our opinion can be safely extracted from the present analysis are the following:

- the data seem to prefer a light Higgs
- a stable determination of the width of the χ^2 parabola at the points $\Delta\chi^2 = \pm 1$ can be given (see fig. 6b). However the position of the minimum sizeably changes depending on the input chosen for the fit. In quantitative terms the expressions $\Delta(\log_{10}(M_{\rm H})) = 0.5$ at the 68% C.L. and $\Delta(\log_{10}(M_{\rm H})) = 1$ at the 95% C.L. can be used to derive an upper limit on the Higgs mass once the value of $M_{\rm H}$ at the minimum is specified.

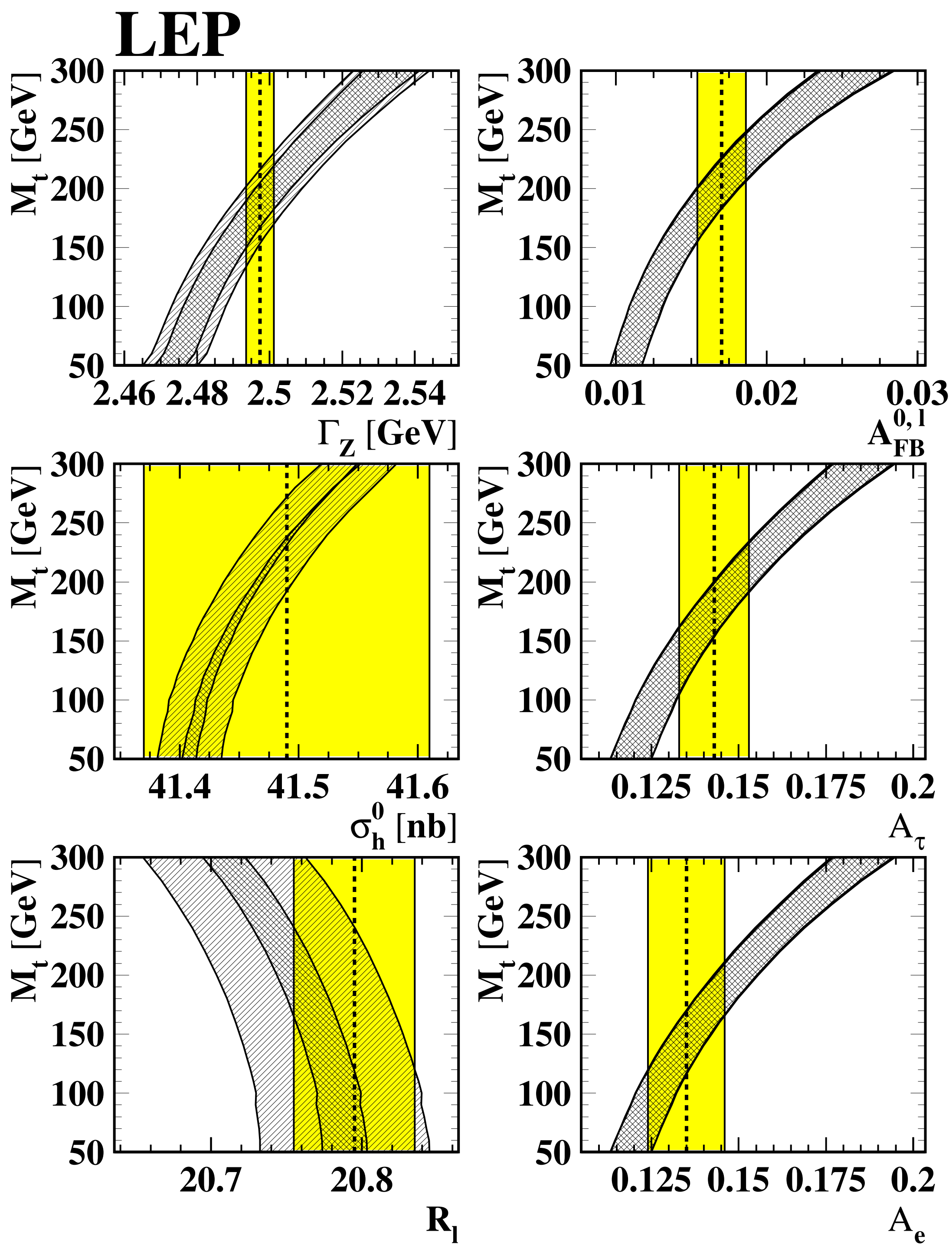

Figure 2: a) Comparison of LEP measurements with the Standard Model prediction as a function of M_t. The cross-hatched area shows the variation of the Standard Model prediction with M_{H} spanning the interval $60 < M_{\mathrm{H}}\,(\mathrm{GeV}) < 1000$ and the singly-hatched area corresponds to a variation of $\alpha_s(M_{\mathrm{Z}}^2)$ within the interval $\alpha_s(M_{\mathrm{Z}}^2) = 0.123 \pm 0.006$. The total width of the band corresponds to the linear sum of both uncertainties. The experimental errors on the parameters are indicated as vertical bands.

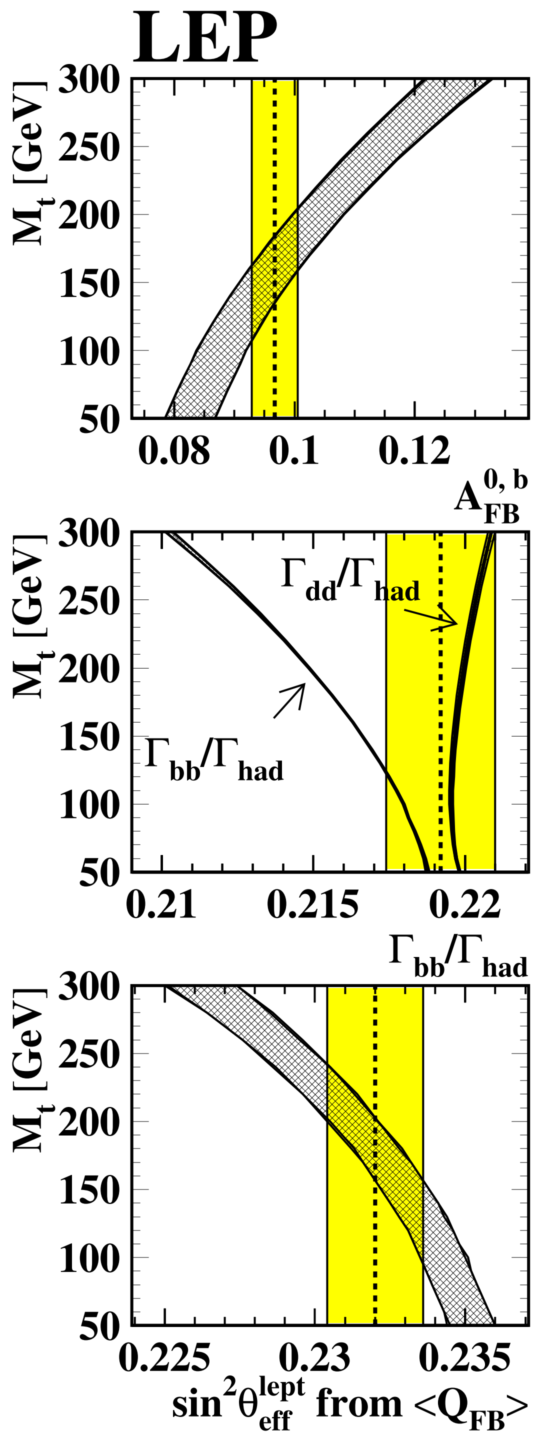

Figure 3: b) Comparison of LEP measurements with the Standard Model prediction as a function of M_t. The cross-hatched area shows the variation of the Standard Model prediction with M_H spanning the interval $60 < M_H\,(\mathrm{GeV}) < 1000$ and the singly-hatched area corresponds to a variation of $\alpha_s(M_Z^2)$ within the interval $\alpha_s(M_Z^2) = 0.123 \pm 0.006$. The total width of the band corresponds to the linear sum of both uncertainties. For the ratios of partial widths, $\Gamma_{b\bar{b}}/\Gamma_{had}$ and $\Gamma_{d\bar{d}}/\Gamma_{had}$, this variation nearly cancels. For the comparison of R_b with the Standard Model the value of R_c has been fixed to the Standard Model. The experimental errors on the parameters are indicated as vertical bands.

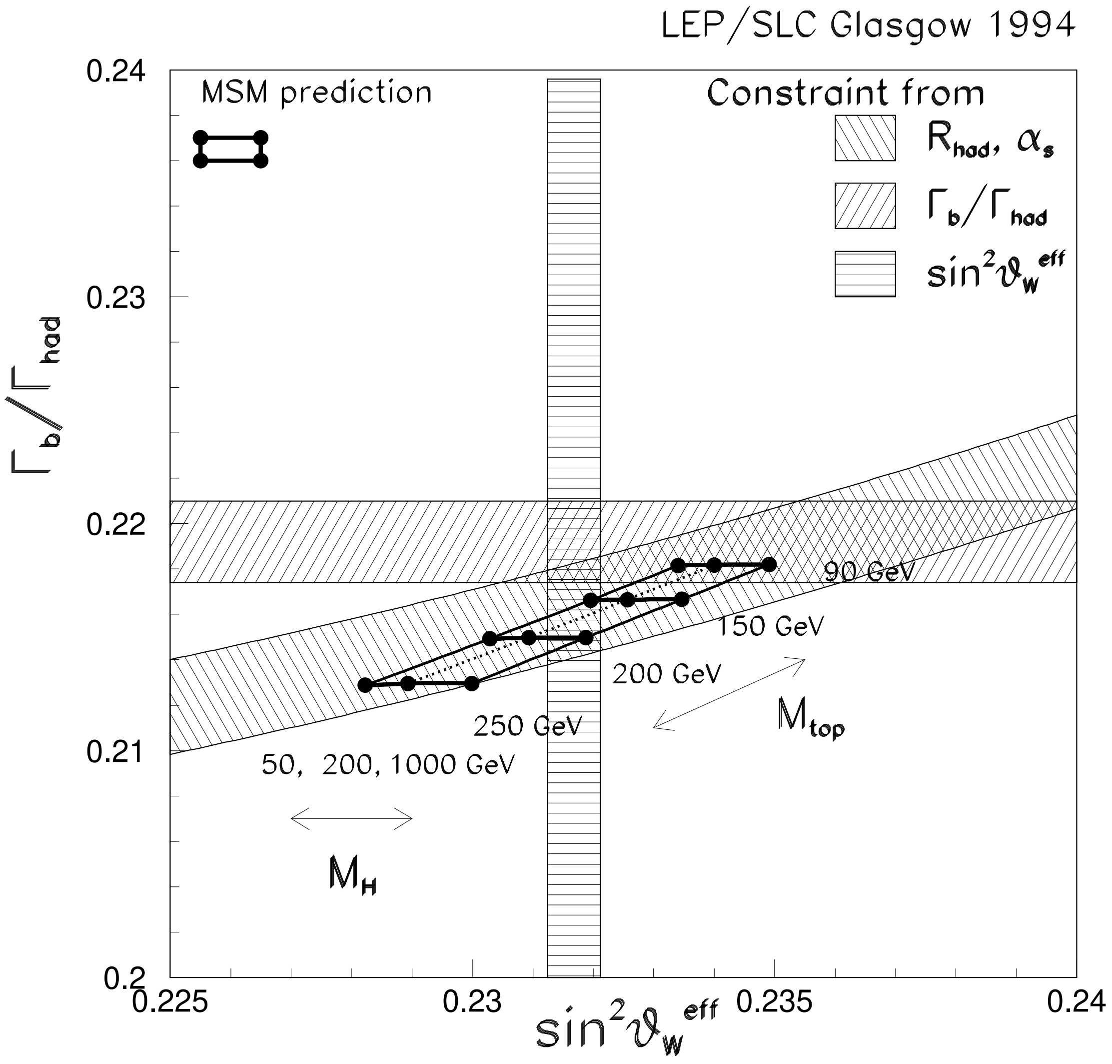

Figure 4: The LEP/SLC measurements of $\sin^2\theta_{eff}^{\mathrm{lept}}$ and R_{b} and the Standard Model prediction. Also shown is the constraint resulting from the measurement of R_ℓ on these variables, assuming the world average $\alpha_s(M_Z^2) = 0.123 \pm 0.006$, as well as the Standard model dependence of light quark partial widths on $\sin^2\theta_{eff}^{\mathrm{lept}}$.

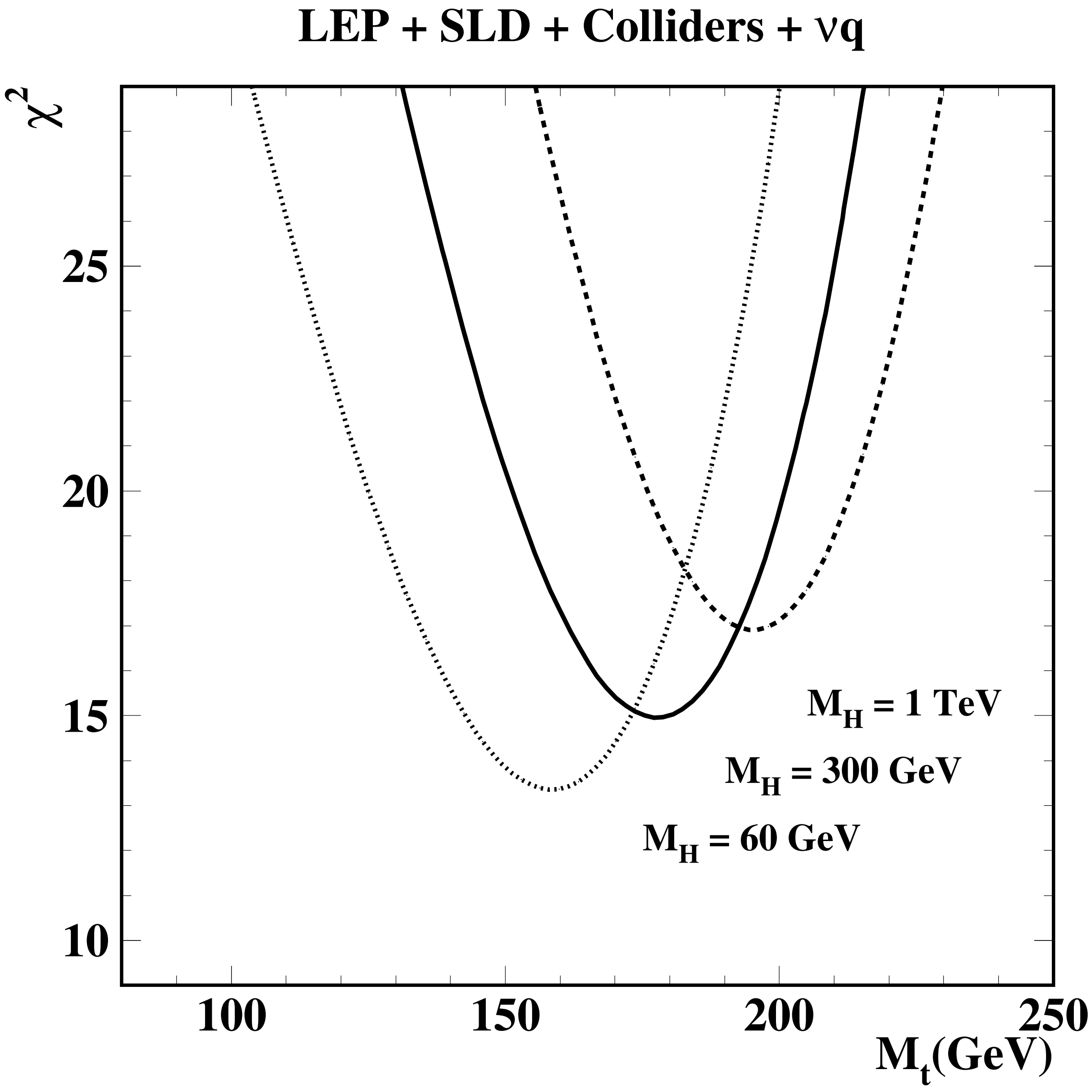

Figure 5: The χ^2 curves for the Standard Model fit in Table 4, column 4 to the electroweak precision measurements listed in Table 3 as a function of M_t for three different Higgs mass values spanning the interval $60 \leq M_H$ [GeV] ≤ 1000.

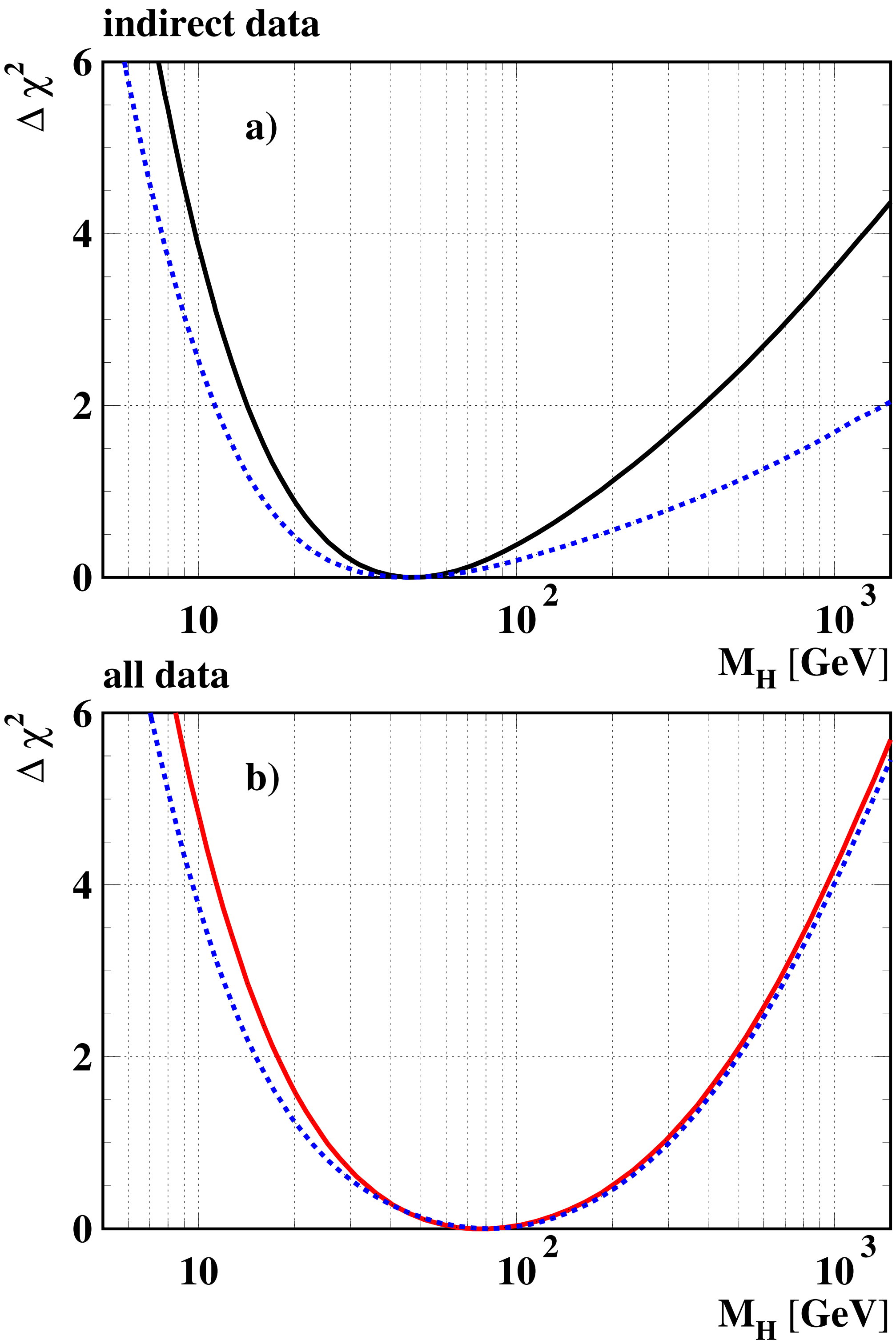

Figure 6: χ^2 vs $\log_{10}(M_{\mathrm{H}})$ as observed in the data (continuous line) and as predicted from theory (dashed line) using all data except CDF (a) and when the CDF determination of M_{t} is also included as an additional constraint in the electroweak fits (b).

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