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THE MASS OF THE TOP QUARK FROM ELECTROWEAK RADIATIVE CORRECTIONS

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ABSTRACT

Measurements of low-energy neutral current parameters and vector boson masses are sensitive to the top quark mass m_t via one-loop radiative corrections in the Standard Model. Assuming the Higgs mass $M_H = M_Z$, the combination of present data imposes $m_t < 153$ GeV at the 68.3% C.L. if the charm quark mass $m_c = 1.45$ GeV, or $m_t < 185$ GeV if m_c is left free. The upper limit on m_t is only weakly sensitive to M_H . The overall χ^2 increases slightly with M_H , but there is no significant upper bound on M_H .

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Main aspects. Precision electroweak measurements are among the most sensitive tests of the Standard Model. As yet, neither the dozens of neutral currents experiments nor the measurements of the $W^\pm$ and Z masses exhibit any deviation from the predictions of the minimal version of the Standard Model, with the neutral current strength parameter $\varrho = 1$ at the tree level and $\sin^2\vartheta_W \simeq 0.23$. Experiments are now so precise that they probe the one-loop radiative corrections in the Standard Model. These are sensitive to the masses of the two particles expected in the minimal Standard Model that have not yet been discovered, namely the top quark and the neutral Higgs boson H . Present e^+e^- data require the top quark mass $m_t > 26$ GeV (this recent upper limit is given by TRISTAN [1]), $p\bar{p}$ collider data [2] indicate that $m_t > 44$ GeV at 95 % C.L. (confidence level), and the measured $B^0\bar{B}^0$ mixing [3] prefers $m_t > 50$ GeV [4]. Bounds on the Higgs mass M_H are weak and porous. Electroweak radiative corrections are not very sensitive to M_H , but vary more rapidly with m_t . Indeed, two global analyses of neutral current data, performed by Amaldi et al. [5] and by Costa et al. [6] have already been used to give upper bounds on m_t with $m_t < 170$ to 200 GeV at 90 % C.L..

In this paper we report a more specific and refined analysis of the effect of taking m_t as a variable in estimating radiative corrections in the different sectors. We look for a possible indication on m_t by comparing the neutral current couplings measured in the following four sectors: (i) ν - q , (ii) ν - e , (iii) e - q , and (iv) $M_{W,Z}$, incorporating the one-loop radiative corrections. In particular, as far as the ν - q sector is concerned, we use a new analysis [7] updating recent deep-inelastic νN scattering data. Within the minimal standard model ($\varrho = 1$), we determine $\sin^2\vartheta_W$ by combining through a least squares method the four different sectors and taking m_t as a variable parameter. As far as m_c and M_H are concerned, our default options are $m_c = 1.5$ GeV and $M_H = M_Z$, but we also discuss the effects of varying these parameters. We find, at the 68.3 % C.L., taking $M_H = M_Z$,

$$\sin^2\vartheta_W = 0.2293 \pm 0.0026 \pm 0.0021 \quad , \quad (1)$$

(the two errors are due to the experimental errors and to the theoretical uncertainties affecting the ν - q sector, respectively). The overall probability distribution is maximized for $m_c \simeq 1.45$ GeV and

$$m_t \sim 75 \text{ to } 85 \text{ GeV} \quad . \quad (2)$$

In general, the χ^2 distribution shows a stationary point, which behaves as a minimum for m_c less

than 1.5 GeV, and reduces to a point of inflection for larger m_c . Its position increases for decreasing m_c and is approximatively independent of M_H . As far as the upper limit on m_t is concerned, we find, again at the 68.3 % C.L. and taking $M_H = M_Z$,

$$m_t < \begin{cases} 152 \text{ GeV} & (m_c = 1.45 \text{ GeV}) \\ 185 \text{ GeV} & (\text{variable } m_c) \end{cases}, \quad (3)$$

with limits slightly larger if the uncertainties affecting the analysis of deep-inelastic scattering are also taken into account. The overall χ^2 increases slightly with M_H , but there is no significant upper bound on M_H .

In the rest of this paper we discuss these conclusions in more detail, discussing first the data in the different electroweak sectors, then considering the effect of taking m_c and M_H as variable parameters in the analysis of the m_t -dependence.

ν - q sector. The four (squared) chiral couplings $u_L^2, d_L^2, u_R^2, d_R^2$ are taken from the final version of the analysis of the structure of the neutral current in the deep-inelastic scattering performed in [7]. This updates the values reported in [6], using new data such as the estimate of R_p published by the CHARM collaboration [8] and the very recent measurements of the individual $\nu p, \nu n, \bar{\nu} p$ and $\bar{\nu} n$ cross-sections reported by the WA25 (BEBC D) Collaboration [9]. Moreover, purely experimental errors are treated separately from theoretical uncertainties. The latter include the value of α_s (or equivalently Λ_{QCD}), the Cabibbo angle, and the parametrizations of the deep-inelastic structure functions. Most importantly, the uncertainties in the threshold behaviour of charm production is considered separately and parametrized by m_c , assuming the slow rescaling suggested by perturbative QCD.

ν - e sector. The two chiral couplings g_L and g_R are calculated starting from the cross-section for the four neutral current processes $\nu_\mu e, \bar{\nu}_\mu e, \nu_e e, \bar{\nu}_e e$. These are essentially the same as those calculated in [10] and used in [6], the only difference being the updated cross-section for $\nu_e e$ given by the LAMPF E225 Collaboration [11]. New data on $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering will soon be provided by the CHARM II Collaboration.

e - q sector. Here we use the SLAC eD and various atomic physics parity violation experiments,

as considered in [6], parametrized in terms of the couplings C_{1u} , C_{1d} and $C_{2u} - \frac{1}{2}C_{2d}$.

Vector boson masses. Here a weighted mean of the masses measured by UA1 [12] and UA2 [13], is used, as in [6].

Radiative corrections. Radiative corrections have been calculated by many authors in the past, in particular by Marciano and Sirlin [14] in a systematic approach that we follow here. Accordingly, the usual approximation is made of neglecting terms $O(\frac{q^2}{M_W^2})$ (where q^2 is the momentum transfer in the specific process considered), as are terms $\sim \frac{m_f^2}{M_W^2}$ where f is any fermion except the top quark. The complete m_t dependence is retained, as are all the logarithmic dependences, including those on $\ln q^2$ in the ν - q and ν - e sectors.

Higgs boson mass. As far as M_H is concerned, much of the analysis is performed assuming $\xi = (M_H/M_Z)^2 = 1$. However, different values for ξ in the range $[0.01, 100]$ will be considered later, and found not to change significantly the preferred range of m_t .

Behaviour of the different sectors. In order to gain an overall impression of the effects of m_t via radiative corrections, we show in Fig. 1 the dependence on m_t of the central values of $\sin^2\vartheta_W$ extracted from the electroweak couplings sector by sector. The errors in the determinations of $\sin^2\vartheta_W$ are not shown, and the constraints from the different sectors are not equally strong, but it is clear that large values of m_t are disfavoured by the growing divergence between the ν - q sector from the one hand, and the other three sectors on the other hand. At present, the dominant contribution to the upper bound on m_t comes from comparing the ν - q and $M_{W,Z}$ sectors, which have the smallest errors. In the near future, the improved CHARM determination of $\sin^2\vartheta_W$ from ν - e scattering with a projected error of ± 0.005 would clearly contribute greatly. Fig. 1 also shows that precision measurements of $\sin^2\vartheta_W$ from parity violation in atomic physics would be very useful for constraining m_t .

Varying m_c at fixed M_H . Let us consider the implications of treating m_c as an unknown parameter. It mainly affects the analysis of couplings in the ν - q sector. We follow the approach of [7], thus including the rather strong correlation between $\sin^2\vartheta_W$ and m_c which was visible in Fig.

15 of ref. [7]. This approach seems more refined than that of reproducing the uncertainty due to m_c as a further error in the central value of $\sin^2\vartheta_W$. Let us first discuss Fig. 2b: for $M_H = M_Z$ fixed, it shows the m_t -dependence of the χ^2 probability distributions for different values of m_c in the range compatible with the analysis of the ν - q sector performed in [7]. The χ^2 distributions for relatively small values of m_c (m_c less than about 1.45 GeV) show a minima at relatively large m_t , minima which become more marked as m_c decreases. For larger values of m_c , the minimum becomes a point of inflection, and the global minimum shifts to the m_t threshold ($m_t \simeq 25$ GeV) for $m_c \simeq 1.50$ GeV. We see that the position of the minimum is clearly anticorrelated with m_c . A more refined analysis shows that the best value of the χ^2 probability is obtained when $m_c = 1.45$ GeV and $m_t \simeq 80$ GeV, values that we take as the optimal ones for these two variables in the analysis. In Fig. 2a the regions of assigned C.L. in the plane (m_t, m_c) are drawn, corresponding to the one-standard-deviation (68.3% C.L.) bounds on m_t and m_c separately. The solid curve includes only the experimental errors, whereas the dashed curve also includes the theoretical uncertainties in the ν - q sector which we have mentioned above. From Fig. 2 it is possible to derive the 68.3% upper bound on m_t : $m_t < 184(196)$ GeV without (with) the inclusion of the theoretical uncertainties affecting the ν - q sector. The limits are somewhat larger than the previous ones estimated in [5] and [6], but it must be remembered that now m_c is taken as a variable parameter, strongly anticorrelated with m_t and therefore affecting the upper limit on m_t (the 90% C.L. upper limit with $m_c = 1.5$ GeV fixed and taking into account the absolute minimum at $m_t \simeq 25$ GeV is $m_t < 176$ GeV, not far from the value given in [6]).

Fixing m_c and M_H . Let us now consider Fig. 3, obtained assuming m_c at its best value, i.e. $m_c = 1.45$ GeV, and maintaining $M_H = M_Z$. The contours in Fig. 3a are one-standard-deviation (68.3% C.L.) bounds on m_t and $\sin^2\vartheta_W$ separately. As before, the solid (dashed) line is the one-standard-deviation contour excluding (including) the theoretical uncertainties in the ν - q sector. They have a negligible effect on the upper bound on m_t , but increase somewhat the errors in $\sin^2\vartheta_W$. The dotted line traces the central value of $\sin^2\vartheta_W$ as a function of m_t , and the small circle indicates the peak of the probability distribution. Fig. 3b shows the projection of the χ^2 probability distribution onto the m_t axis. The solid (dashed) lines again indicate the values of χ^2 excluding (including) theoretical uncertainties in the ν - q sector. There is a minimum of χ^2 at $m_t \simeq 80$ GeV, and a local maximum at $m_t \simeq 60$ GeV. As mentioned above, the 68.3% C.L. upper limit on m_t is $m_t < 152(154)$ GeV, without (with) the theoretical uncertainties. The

corresponding 90 % C.L. upper limit is $m_t < 188$ (193) GeV.

Varying the Higgs mass. Finally, we record in Fig. 4 the sensitivity of present neutral current measurements to the Higgs boson mass M_H , taking $m_c = 1.45$ GeV and relaxing the previous default value $\xi = (M_H/M_Z)^2 = 1$. We show in Fig. 4a the family of the one-standard-deviation (on each variable separately) contours in the $(m_t, \sin^2\vartheta_W)$ plane for different values of ξ in the range $[0.01, 100]$ corresponding to M_H in the range $[\sim 10, \sim 1000]$ GeV. The envelope of the regions plotted in Fig. 4a delimits the region of assigned C.L. for ξ taken arbitrarily in the range $[0.01, 100]$. Fig. 4b shows the χ^2 probability distributions for m_t with different choices of ξ . The minimum of the χ^2 distribution is for $\xi = 0.01$, with $m_t \simeq 80$ GeV and $\sin^2\vartheta_W = 0.2281$. We see that the central values of $\sin^2\vartheta_W$ and m_t both increase very slightly with M_H . We also see that the local maximum at $m_t \sim 60$ GeV becomes slightly more pronounced as ξ increases.

Conclusions. We have seen in this paper how electroweak radiative corrections in the Standard Model already may give some indication on m_t , even when theoretical uncertainties in the interpretation of neutral current data are taken into account, and m_c and M_H are allowed to vary freely. A preferred value of m_t around 80 GeV can be extracted, while the 68.3 % C.L. upper limit on m_t varies between ~ 150 GeV and ~ 190 GeV, depending on the assumptions made. Although encouraging to experimentalists, the slight preference for small M_H detectable in Fig. 4b is not yet statistically significant.

We can expect the CHARM II experiment soon to provide improvements in our constraints on m_t , m_c and M_H . It is apparent from Fig. 1 that a high-precision measurement of $\sin^2\vartheta_W$ from $\nu_\mu - e$ and $\bar{\nu}_\mu - e$ scattering offers the best prospects for pinning down m_t in the near future. Almost equally powerful would be a precision determination of $\sin^2\vartheta_W$ from parity violation in atoms. In the somewhat longer term, precision measurements of M_W and M_Z , and of neutral current parameters at the Z^0 peak, offer the best prospects for determining m_t and M_H indirectly. It remains to be seen whether the top quark and the Higgs boson are detected directly before precision electroweak measurements tell us where to look for them.

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References

- [1] H. Yoshida et al., Phys. Lett. **198B** (1987) 570;
H. Sagawa et al., Phys. Rev. Lett. **60** (1988) 93;
I. Adachi et al., Phys. Rev. Lett. **60** (1988) 97.
- [2] C. Albajar et al., UA1 Collaboration, Z. Phys. C – Particles and Fields **37** (1988) 505.
- [3] H. Albrecht et al., ARGUS Collab., Phys. Lett. **192B** (1987) 245.
- [4] G. Altarelli, in *Proceedings of the International Europhysics Conference on High Energy Physics* O. Botner ed. (Uppsala, 1987) p. 1002, and refs. therein.
- [5] U. Amaldi, A. Bohm, L.S. Durkin, P. Langacker, A.K. Mann, W.J. Marciano, A. Sirlin and H.H. Williams, Phys. Rev. **D36** (1987) 1385.
- [6] G. Costa, J. Ellis, G.L. Fogli, D.V. Nanopoulos and F. Zwirner, Nucl. Phys. **B297** (1988) 244.
- [7] G.L. Fogli and D. Haidt, Bari preprint BA-TH/2-88 (1988), to appear in Z. Phys. C – Particles and Fields.
- [8] CHARM Collaboration, J.V. Allaby et al., Z. Phys. C – Particles and Fields **36** (1987) 611.
- [9] WA 25 Collaboration, D. Allasia et al., Saclay preprint DPhPE 88-03 (1988).
- [10] G.L. Fogli, Europhys. Lett. **4** (1987) 527.
- [11] LAMPF Collaboration, presented by R.C. Allen, *Proceedings of the 13th International Conference on Neutrino Physics and Astrophysics* (Boston, 1988) to appear.
- [12] UA1 Collaboration, C. Albajar et al., Phys. Lett. **185B** (1987) 233; **191B** (1987) 462A.
- [13] UA2 Collaboration, R. Ansari et al., Phys. Lett. **186B** (1987) 440.
- [14] W.J. Marciano and A. Sirlin, Phys. Rev. **D22** (1980) 2695; **E D31** (1985) 213;
A. Sirlin and W.J. Marciano, Nucl. Phys. **B189** (1981) 442;
W.J. Marciano and A. Sirlin, Phys. Rev. **D29** (1984) 945; **E D31** (1985) 213.

Fig. 1 — The dependence on m_t of the central value of $\sin^2\theta_W$ extracted from the different sectors considered: ν -q, ν -e, e-q and the vector boson masses (VBM). Note the differences at large m_t . The curves are obtained assuming $m_c = 1.5$ GeV and $M_H = M_Z$.

Fig. 2 — a) The allowed regions in the (m_t, m_c) plane showing the $1-\sigma$ limit on each of the two variables separately, extracted from a global analysis of $\sin^2\theta_W$ performed on all the four sectors and assuming $M_H = M_Z$. The solid (dashed) line is obtained without (with) the inclusion of the theoretical uncertainties mentioned in the text. b) The χ^2 probability distribution as a function of m_t , for different values of m_c (expressed in GeV) and $M_H = M_Z$.

Fig. 3 — a) The allowed regions in the $(m_t, \sin^2 \theta_W)$ plane showing the $1\text{-}\sigma$ limit on each of the two variables separately, extracted from a global analysis performed on all the four sectors, assuming $M_H = M_Z$ and $m_c = 1.45$ GeV. b) The χ^2 probability distribution as a function of m_t , for $m_c = 1.45$ GeV and $M_H = M_Z$. In both both a) and b) the solid (dashed) curve is obtained without (with) the inclusion of the theoretical uncertainties mentioned in the text.

Fig. 4 — a) The m_t -dependence of $\sin^2 \theta_W$ extracted from a global fit to all sectors, for $m_c = 1.45$ GeV and for different values of $\xi = M_H^2/M_Z^2$. b) The χ^2 probability distribution as a function of m_t , for $m_c = 1.45$ GeV and different values of $\xi = M_H^2/M_Z^2$.