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THE IMPLICATIONS OF RECENT ELECTROWEAK DATA FOR m_t AND M_H

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ABSTRACT

We report the results of a new global fit to electroweak data, including the recent SLC, CDF and UA2 measurements of M_Z , the new CDF and UA2 values of M_W/M_Z , and the new CHARM II measurement of $\sigma(\bar{\nu}_\mu e)/(\sigma(\nu_\mu e))$. The precision measurement of M_Z enforces a strong negative correlation between $\sin^2\theta_W$ and m_t , and we find

$$\sin^2\theta_W = 0.2276^{+0.0039}_{-0.0034}, \quad m_t = 132^{+31}_{-37} \text{ GeV.}$$

The electroweak data also prefer $M_H < M_Z$, but not at a high level of significance.

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As in our previous papers, we group the available electroweak data into 4 sectors: (i) $\nu - q$, (ii) $\nu - e$, (iii) $e - q$, and (iv) $M_{W,Z}$. We now discuss each of these sectors in turn, pointing out key features and new developments.

$\nu - q$ sector. Here there are no new data, and we use again the complete analysis of neutral currents in deep-inelastic νN scattering reported in [8]. Since it is the almost m_t -independent value of $\sin^2 \theta_W$ extracted from these data that dominates the comparison with the m_t -dependent high-energy data, we discuss in some detail the uncertainties in the $\nu - q$ sector. The estimates of the four (squared) chiral couplings $u_L^2, d_L^2, u_R^2, d_R^2$ in ref. [8] include both the experimental errors and all theoretical uncertainties due to the parametrization of deep-inelastic scattering within the parton model with QCD effects. In particular, the effect was considered of varying m_c , which influences the threshold of charm production in the charged-current sector. A fit to the deep-inelastic charged and neutral current νN scattering data alone does not constrain m_c very tightly: $m_c = 1.54 \pm 0.33$. However, there is independent information on m_c from the perturbative QCD analysis of other hard processes and a recent review [9] quotes $m_c = 1.35 \pm 0.05$ GeV. Accordingly we have assumed $m_c = 1.45$ GeV, which is the value for which we found the best value χ^2 in the $\sin^2 \theta_W$ analysis of all sectors in [2]. Values of m_c between 1.35 and 1.55 GeV would give results well within the errors we quote. The other theoretical uncertainties include the parametrization of the deep-inelastic structure functions, the value of α_s (or equivalently Λ_{QCD}), and the generalized Cabibbo angles. Structure function parametrizations similar to those discussed by Buras and Gaemers were used in [8]. They are adequate for our purposes: parametrizations incorporating all leading and next-to-leading order QCD effects would be too cumbersome for convenient fitting and would not change the results outside the quoted errors. The most important contributions to these include the uncertainty in the strange sea quoted in [8], an allowance for a deviation from the perturbative QCD value of σ_L/σ_T by ± 0.1 , and errors in the MINUIT fit parameters. We take $\Lambda_{QCD} = 0.25 \pm 0.18$ to cover a wide range of values. As for the generalized Cabibbo angles, we assume effective unitarity among the first two generations, in which case all matrix elements can be expressed in terms of the Cabibbo angle, for which we take $\cos \theta_c = 0.9744 \pm 0.0010$.

Experimental probes of the electroweak sector of the Standard Model are entering a new era with the advent of precision data from the Z^0 peak. However, it should not be forgotten that useful information can still be obtained by comparing these data with low-energy neutral current measurements. There have been two global analyses of electroweak data, mainly on neutral currents [1], and we have discussed how these data can be used to constrain the top quark mass m_t [2], taking into account both experimental and theoretical uncertainties such as those in the charm quark mass m_c and the Higgs boson mass M_H . More recently [3], we have discussed the interesting constraint on the top quark mass m_t that could be obtained by combining a future high-precision measurement of M_Z with the existing low-energy neutral current data. We showed that if M_Z were measured with an error ± 50 MeV, then $m_t \simeq 95 \text{ GeV} + 66 (91.6 \text{ GeV} - M_Z) \pm O(35) \text{ GeV}$.

Since our paper was written, several new electroweak measurements have been published, including (a) a new measurement of $\sin^2 \theta_W$ from comparing $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering [4], (b) new measurements of M_W/M_Z by the CDF [5] and UA2 [6] collaborations, and most importantly (c) new measurements of M_Z by the Mark II collaboration at SLC [7], by the CDF collaboration [5], and by the UA2 collaboration [6].

In this paper we report the results of a new global analysis of electroweak data, including all the new measurements. Since they are crucial for the interpretation of the low-energy data, we also review briefly the systematic errors in the analysis of deep-inelastic νN scattering. Even though the present SLC errors on M_Z are still considerably larger than the conjectural ones we assumed in [3], we find a qualitatively similar conclusion, namely that m_t is fixed with an error of less than 40 GeV, if one assumes the minimal standard model to be correct:

$$m_t = 132^{+31}_{-37} \text{ GeV} \quad (1)$$

We also comment on the mass of the Higgs boson M_H in the light of our analysis.

$\nu - e$ sector. Here the most significant new development has been a determination of $\sin^2\theta_W$ from the ratio $\sigma(\bar{\nu}_\mu e)/\sigma(\nu_\mu e)$ by the CHARM II collaboration [4]:

$$\sin^2\theta_W = 0.233 \pm 0.012 \pm 0.008 \quad , \quad (2)$$

before the application of radiative corrections. The latter decrease the preferred value of $\sin^2\theta_W$ as a function of m_t when it exceeds $\simeq 50$ GeV, in a manner qualitatively similar to their effect on $\sin^2\theta_W$ as derived from the vector boson masses, and therefore do not provide a long lever arm for determining m_t by comparison with the vector boson masses. However, we remind the reader that this determination of $\sin^2\theta_W$ is immune to the type of vexing theoretical uncertainties discussed above in connection with νN scattering. The new result of CHARM II [4] has been combined with the previous estimate of the chiral leptonic couplings considered in [3] and discussed in [10].

$e - q$ sector. Apart from a recent estimate of $\sin^2\theta_W$ from the forward-backward asymmetry for $\bar{p}p \rightarrow (Z^0 \rightarrow e^+e^-) + X$ for which radiative corrections are not available, there has been no significant new experimental development since the high-precision measurement of parity violation in Cesium by the Boulder group [11]. We use the analysis of these and other $e - q$ neutral current data made in [12].

M_W, Z sector. It is here that the most dramatic new experimental developments have occurred. The most precise has been a new measurement of M_Z by the Mark II collaboration at the SLC [7]:

$$M_Z = 91.17 \pm 0.18 \text{ GeV} \quad , \quad (3)$$

including systematic errors of 0.04 GeV due to the absolute energy scale uncertainty and 0.05 GeV due to the uncertainty in the miniSAM efficiency. Also significant has been a new measurement of M_Z by the CDF collaboration at the FNAL Tevatron collider [5]:

$$M_Z = 90.9 \pm 0.3 \pm 0.2 \text{ GeV} \quad , \quad (4)$$

where the former error includes both statistics and systematics, and the latter is an energy scale error. There has also been a new measurement of M_Z by the UA2 collaboration [6],

$$M_Z = 90.2 \pm 0.6 \pm 1.4 \text{ GeV} \quad . \quad (5)$$

In our analysis we take into account all the above measurements, evidently dominated by the estimate (3) of the Mark II collaboration: by combining all the errors in quadrature we obtain

$$M_Z = 91.09 \pm 0.16 \text{ GeV} \quad . \quad (6)$$

Two new measurements of M_W have also been made, by the CDF collaboration [5]:

$$M_W = 80.0 \pm 0.2(\text{stat}) \pm 0.5(\text{syst}) \pm 0.3(\text{scale}) \text{ GeV} \quad , \quad (7)$$

and by the UA2 collaboration [6]:

$$M_W = 80.0 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 1.2(\text{scale}) \text{ GeV} \quad . \quad (8)$$

They not only contribute to the analysis of $\sin^2\theta_W$ in terms of m_t in the VBM sector, but, more importantly, they allow through the ratio M_W/M_Z a rather accurate determination of $\sin^2\theta_W$ independently of m_t (see Fig. 1), since the overall energy scale errors drop out of the ratio, which is dominated by statistical errors and by systematic errors in the procedure for extracting M_W from the observed lepton p_T -distribution.

We now discuss the results of our global fit to the electroweak data. Fig. 1 shows the m_t -dependence of the central values of $\sin^2\theta_W$ inferred from the various sectors above, which can be compared with our previous figures of this type. Two significant effects are noticeable. One is that M_Z (eq. (6)) is now somewhat below the previous central value, although well within the errors stated previously [2]. This increases the value of $\sin^2\theta_W$ extracted from the vector boson mass sector for any fixed value of m_t . Since the value of $\sin^2\theta_W$ extracted from the $\nu - q$ sector is not strongly dependent on m_t , the net effect is to shift the optimal value of m_t to a higher value. The error in $\sin^2\theta_W$ inferred from the direct measurement of M_W/M_Z is much larger than that inferred from M_Z alone, and is shown as an error bar on the left-hand side of the figure. However, it goes in the direction of decreasing $\sin^2\theta_W$ and hence increasing the preferred value of m_t . We also observed that the VBM and $\nu - e$ central values of $\sin^2\theta_W$ are now coincident for $m_t \sim 200$ GeV, although the errors in the latter sector still do not permit a definite conclusion to be drawn from this comparison alone.

As advertized above, the principal constraint on m_t comes from the comparison between the $\nu - q$ and VBM sectors, by virtue of their smaller errors and the different m_t -dependences of the inferred values of $\sin^2\theta_W$. Fig. 2 plots again their central values of $\sin^2\theta_W$, together with their error bands. It is the limited range of overlap between these bands that is the driving force behind our bounds (1) on m_t . The extent of this overlap is almost independent of the error in the VBM sector due to the uncertainty in measuring M_Z , as soon as this error becomes significantly less than that from the $\nu - q$ sector. This explains why our bounds (1) are very similar to those given in [3] for the same central value of M_Z , even though the present error in M_Z is considerably larger than what we had assumed previously.

We have already discussed why we believe the errors we quote on $\sin^2\theta_W$ in the $\nu - q$ sector to be realistic. It is clear from Figs. 2 and 3 that even if the $\nu - q$ errors were somewhat increased, e.g. to reflect uncertainty on m_c , the essential features of significant lower and upper bounds on m_t would be maintained. On the one hand, we see in Fig. 2 that the CDF and UA2 measurements of M_W/M_Z would prevent m_t from being much smaller than 100 GeV. On the other hand, we see in Fig. 3 that consistency in the low-energy sectors between $\nu - q$, $e - q$ and $\nu - e$ data would prevent m_t from being much greater than 180 GeV, and that consistency between the VBM and $\nu - q$ sectors could not long be maintained because of their divergent dependences of $\sin^2\theta_W$ on m_t . As an exercise, we nevertheless made a notional global fit in which the $\nu - q$ errors in the chiral quark couplings were arbitrarily inflated by 50%. We found that the central value of m_t was increased by 8 GeV, because of the stronger relative weights of the VBM, $\nu - e$ and $e - q$ sectors that prefer large m_t . The upper (lower) bound of m_t is increased (decreased) by 8 (11) GeV.

Using the preferred errors quoted earlier and combining all 4 sectors we obtain the final contour in the $(m_t, \sin^2\theta_W)$ plane and χ^2 -distribution as a function of m_t shown in Fig. 4. In the top part of the figure we see again the strong negative correlation between m_t and $\sin^2\theta_W$ which has been imposed by the precision measurement of M_Z . Leaving m_t ,

as a free parameter, we find

$$\sin^2\theta_W = 0.2276^{+0.0039}_{-0.0034}, \quad (9)$$

whose central value is very close to that we quoted previously [3] before M_Z was measured so precisely. As for m_t , we find

$$m_t = 132^{+31}_{-37} \text{ GeV}, \quad (10)$$

as already reported in eq. (1). It is a non-trivial check on the consistency of the Standard Model, including radiative corrections, that this favoured range of m_t is compatible with the lower bounds established by the $\bar{p}p$ colliders at FNAL and CERN ($m_t > 78$ GeV at 90 % C.L. from CDF [13], $m_t > 67$ GeV at 95% C.L. from UA2 [14], $m_t > 65$ GeV at 95% C.L. from UA1 [15]).

In all the above analysis, we have taken as our default option $M_H = M_Z$. We have previously reported [2] on a very slight preference for small M_H on the basis of the electroweak data available last year. This very slight preference is maintained this year, but is still not significant. Fig. 5 compares the χ^2 distributions for $\xi \equiv (M_H/M_Z)^2 = 0.01$ (dotted line), 1 (solid line) and 100 (dashed line). The shifts in the optimal value of m_t are +5 GeV for $\xi = 0.01$ and -10 GeV for $\xi = 100$, which are still small compared with the other sources of error in m_t included in the range quoted in the eqs. (1) and (10).

Further advances in the measurement of electroweak parameters will mainly come from high-precision measurements at the Z^0 peak in e^+e^- annihilation, although precision low-energy measurements in $\nu - e$ scattering and atomic physics parity violation will also be important. As noted above, it is already a non-trivial consistency check on the standard electroweak theory that the high values of m_t favoured by this analysis of radiative corrections are consistent with the lower limits on m_t recently established by the $\bar{p}p$ colliders. It is quite possible that our information about m_t will continue for some time to be indirect, although discovery of the top quark at the FNAL $\bar{p}p$ collider or at LEP II still appears possible.

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Fig. 1 — The dependences on m_t of the central values of $\sin^2 \theta_W$ extracted from present data in the different sectors considered: $\nu-q$, $\nu-e$, $e-q$ and the vector boson masses (VBM). The error on $\sin^2 \theta_W$ from measurements of M_W/M_Z is shown as a vertical error bar as well as being included in the VBM sector. Note the differences between the sectors at large m_t . We have assumed $m_c = 1.45$ GeV and $M_H = M_Z$. This figure updates Fig. 1 of ref. [3].

Fig. 2 — Allowed regions in the $(m_t, \sin^2 \theta_W)$ plane showing the $1-\sigma$ limit on each of the two variables separately for the VBM and $\nu-q$ sectors. Note that the measured value of M_W/M_Z favours $m_t > 95$ GeV. We continue to take $m_c = 1.45$ GeV and $M_H = M_Z$.

Fig. 3 — Allowed regions in the $(m_t, \sin^2 \theta_W)$ plane showing the $1-\sigma$ limit on each of the two variables separately for the VBM and low-energy ($\nu - q$, $\nu - e$ and $e - q$) sectors. Note that the latter alone favour $m_t < 180$ GeV. We continue to take $m_c = 1.45$ GeV and $M_H = M_Z$.

Fig. 4 — a) Allowed region in the $(m_t, \sin^2 \theta_W)$ plane showing the $1-\sigma$ limit on each of the two variables separately when data from all sectors are included, and b) the χ^2 distribution as a function of m_t , both for $m_c = 1.45$ GeV and $M_H = M_Z$.

Fig. 5 --- The χ^2 distributions as a function of m_t for different choices of $\xi = M_H^2/M_Z^2$.