Consequences of Recent Electroweak Data and W-mass for the Top Quark and Higgs Masses

Kyungsik Kang

Department of Physics, Brown University, Providence, RI, 02912 USA

and

Sin Kyu Kang

Department of Physics, Seoul National University, Seoul, Korea

ABSTRACT

We critically reexamine the precision tests of the standard model by coupling the current world average value of $M_W$ with the recent LEP electroweak data with the aid of a modified ZFITTER program to include the dominant two-loop and QCD-EW mixed terms. The results show a clear evidence of nonvanishing electroweak radiative corrections. The recent CDF $m_t$ is a solution of the minimal $\chi^2$-fits to the recent LEP data set and $M_W = 80.23(18)$ GeV but with a heavy Higgs scalar, i.e., $m_t = 179$ GeV and $m_H = 300$ GeV. We discuss how sensitive $m_t$ and $m_H$ are depending on the exact value of $M_W$ even within the present uncertainty, as well as on $\alpha_s$ and $\alpha(M_Z)$. We show how the future improvements on $M_W$ can discriminate different values of $m_t$ and $m_H$ from the electroweak data and provide a crucial and decisive test for the standard model.

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Recent experimental advances, namely, the new measurements of $M_W$ [1], the improved LEP precision data [2], and the evidence of $m_t$ from CDF [3], coupled with the theoretical progress [4,5] on the dominant two-loop and QCD-EW mixed terms, call for a critical reexamination of the precision tests of the standard model (SM). We would like to report on the new results of the precision tests of the SM based on these new experimental and theoretical informations and discuss implication on the top quark and Higgs masses as a consequence. Though global tests of the SM with the electroweak radiative corrections (EWRC) against the electroweak data from LEP, SLC and elsewhere have been carried out by several group [6], the sensitivity of the tests to the exact value of the W-boson mass [7] as well as to $\alpha_s$ and $\alpha(M_Z)$ has perhaps not been fully recognized. For this reason we discuss in particular how the future improvements on $M_W$, $\alpha_s$ and $\alpha(M_Z)$ can provide a crucial test of the SM by extrapolating the consequences of the current level of accuracy in the LEP electroweak data [2] and the new world average value of $M_W$ [1]. Also the $m_t$ - $M_W$ correlation for different values of $m_H$ coming from the full EWRC, when compared to the best fit solutions as well as the current experimental values of $m_t$ and $M_W$, reveals intriguing aspects of the precision tests for the SM and of the prospect for new physics. The full EWRC including the dominant two-loop and QCD-EW mixed terms are calculated and the minimal $\chi^2$-fits to the data are made by using a modified ZFITTER program [8] with the improved QCD correction factor.

The basic electroweak parameters used in the numerical calculations are the hyperfine structure constant, $\alpha = \frac{e^2}{\pi} = 1/137.0359895(61)$, the four-fermion coupling constant of the $\mu$-decay, $G_\mu = 1.16639(2) \times 10^{-5}$ GeV$^{-2}$, and Z-mass which we take $M_Z = 91.1888(44)$ GeV. Compared to the Z-mass, the W-mass is yet to be improved, i.e., we have at best $M_W = 80.21(16)$ GeV after combining the CDF measurement $M_W = 80.38(23)$ GeV or the new world average value $M_W = 80.23(18)$ GeV [1]. Numerical computations of the full EWRC require the mass values of the leptons, quarks, Higgs scalar, as well as $\alpha_s$ besides these quantities. The minimal $\chi^2$-fits to the data therefore can give only correlations among $M_W$, $m_t$ within the experimental uncertainties and $m_H$ for the given $\alpha_s$ and $\alpha(M_Z)$. The latter has a substantial uncertainty coming from the hadronic contributions and can cause significant shifts in the output solutions. We report here the results of the minimal $\chi^2$-fits to the 1994 data set [2] of the Z-decay parameters measured at LEP and to $M_W = 80.23(18)$ GeV.

One has, in the SM, the on-shell relation $\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$, and the four-fermion coupling constant $G_\mu$

$$G_\mu = \frac{\pi \alpha}{\sqrt{2} M_W^2} \left( 1 - \frac{M_W^2}{M_Z^2} \right)^{-1} \frac{1}{1 - \Delta r}$$  \hspace{1cm} (1)
so that $\Delta r$, representing the radiative corrections, is given by

$$\Delta r = 1 - \left( \frac{A}{M_W} \right)^2 \frac{1}{1 - M_W^2 / M_Z^2}$$

(2)

where $A = 37.2802 \pm 0.0003$.

We have found [7] that the radiative correction $\Delta r$ is sensitive to the value of $M_W$. Mere change in $M_W$ by 0.59% can result as much as 75% in $\Delta r$. Also precise determination of the on-shell value of $\sin^2 \theta_W$ can constrain the needed value of $\Delta r$ and $M_W$. The partial width for $Z \rightarrow f \bar{f}$ is given by

$$\Gamma_f = \frac{G_F M_Z^3}{\sqrt{2} 24\pi} \beta R_{\text{QED}} c_f R_{\text{QCD}} (M_Z^2) \left\{ (\bar{a}_f^Z)^2 + (\bar{s}_f^Z)^2 \right\} \times \left( 1 + 2 \frac{m_f^2}{M_Z^2} \right) - 6(\bar{a}_f^Z)^2 \frac{m_f^2}{M_Z^2}$$

(3)

where $\beta = \beta(s) = \sqrt{1 - 4m_f^2 / s}$ at $s = M_Z^2$, $R_{\text{QED}} = 1 + \frac{3}{4} \alpha Q_f^2$, $R_{\text{QCD}} = 1 + 1.05 \bar{a}_f + 0.9(\pm 0.1) \left( \frac{\bar{a}_f}{\bar{a}_s} \right)^2 - 13.0 \left( \frac{\bar{a}_f}{\bar{a}_s} \right)^3$ for the light quarks [9] and $R_{\text{QCD}} = 1 + c_1(m_b) \bar{a}_s + c_2(m_b, m_t) \left( \frac{\bar{a}_f}{\bar{a}_s} \right)^2 - 13.0 \left( \frac{\bar{a}_f}{\bar{a}_s} \right)^3$ for b quarks [8], with the gluonic coupling constant $\bar{a}_s(M_Z^2) = 0.123 \pm 0.006$ [9], and the color factor $c_f = 3$ for quarks and 1 for leptons. Here the renormalized vector and axial-vector couplings are defined by $\bar{a}_f^Z = \sqrt{\rho_f^Z 2\alpha_f^Z} = \sqrt{\rho_f^Z 2I_3}$ and $\bar{s}_f^Z = \bar{a}_f^Z [1 - 4|Q_f| \sin^2 \theta_W \kappa_f^Z]$ in terms of the familiar notations [8,10]. It is customary that all non-photonic and pure weak loop corrections in the vertices and box diagrams are grouped in $\rho_f^Z$ and $\kappa_f^Z$ along with the propagator corrections due to t-quark and Higgs, while all other radiative corrections in the propagators are contained in the couplings through $G_F$. Experimentally, the renormalized vector and axial-vector couplings are obtained from the data after removing all photonic contributions.

The results of the best global fit to the data are given in Table 1. One gets a stable output $M_W = 80.37 \pm 0.02$ GeV and $m_t = 179 \pm 17$ GeV for a Higgs in the range of $m_H = 60 - 1000$ GeV and sees a clear effect of the EWRC. In general the $\chi^2$-values tend to prefer lower $m_t$ and accordingly smaller $m_H$, though any pair of $(m_t, m_H)$ on the Best.fit curve in Fig. 1 is statistically comparable. The Best.fit curve in Fig. 1 is obtained for $M_W = 80.23$ GeV, $\alpha_s(M_Z) = 0.123$ and $\alpha(M_Z) = 1/128.786$. Fig. 2 shows how $M_W$ changes with $m_t$ for a fixed $m_H$ from the full EWRC, along with the minimal $\chi^2$-fit solutions ($\Diamond$ points) as well as the world average $M_W$ and CDF $m_t$ for comparison. However the Best.fit curve in Fig. 1 and the $\Diamond$ points in Fig. 2 can have as much as $\pm 6$ GeV and $\pm 40$ MeV shifts in $m_t$ and $M_W$ respectively due to the uncertainty $\Delta \alpha_s(M_Z) = \pm 0.006$. Also there can be additional downward shifts by 5 GeV and 20 MeV respectively upon $\alpha(M_Z)$ decreasing to 1/128.855. Note from Fig. 2 that a higher $M_W$ is preferred for a lighter Higgs but to distinguish a shift of 200 GeV in $m_H$ at $M_W = 80.23$ GeV one will need an improvements of about 50 MeV for the W-mass, i.e., better than the theoretical
| Parameter          | Experiment | Full EW | Full EW | Full EW |
|--------------------|------------|---------|---------|---------|
| $m_t$ (GeV)        | 174 ± 10^{+13}_{-12}$ | 195     | 179     | 162     |
| $m_H$ (GeV)        | 60 ≤ $m_H$ ≤ 1000 | 1000    | 300     | 60      |
| $M_W$ (GeV)        | 80.23 ± 0.18 | 80.39   | 80.36   | 80.35   |
| $\Gamma_Z$ (MeV)  | 2497.4 ± 3.8 | 2499.1  | 2499.0  | 2498.3  |
| $\sigma_h^P (nb)$ | 41.49 ± 0.12 | 41.42   | 41.40   | 41.39   |
| $R(\Gamma_{\text{had}}/\Gamma_{\bar{t}t})$ | 20.795 ± 0.040 | 20.776  | 20.792  | 20.811  |
| $A_{FB}^{0,l}$     | 0.0170 ± 0.0016 | 0.0155  | 0.0156  | 0.0159  |
| $A_t$              | 0.143 ± 0.010  | 0.140   | 0.140   | 0.141   |
| $A_e$              | 0.135 ± 0.011  | 0.140   | 0.140   | 0.141   |
| $R(\Gamma_{bb}/\Gamma_{\text{had}})$ | 0.2202 ± 0.0020 | 0.2146  | 0.2152  | 0.2158  |
| $R(\Gamma_{cc}/\Gamma_{\text{had}})$ | 0.1583 ± 0.0098 | 0.1713  | 0.1712  | 0.1711  |
| $A_{FB}^{0,b}$     | 0.0967 ± 0.0038 | 0.0930  | 0.0932  | 0.0943  |
| $A_{FB}^{0,c}$     | 0.0760 ± 0.0091 | 0.0596  | 0.0596  | 0.0605  |
| $\sin^2 \theta_{\text{eff}}^{\text{lep}}$ from $<Q_{FB}>$ | 0.2320 ± 0.0016 | 0.2319  | 0.2319  | 0.2317  |
| $\chi^2$          | 16.5        | 14.4    | 12.1    |
| $\Delta r$        | 0.0443 ± 0.0102 | 0.0350  | 0.0363  | 0.0374  |

Table 1: Numerical results including full EWRC for 11 experimental parameters and $M_W$. Each pair of $m_t$ and $m_H$ represents the case of the best $\chi^2$- fit to the improved 1994 LEP data [2] and $M_W = 80.23 ± 0.18$ GeV [1].
uncertainty of the current precision tests. This ambiguity in $M_W$ is about the level of the accuracy aimed at LEP-200 and therefore the expected $m_t$ improvement at LEP-200 will be at the best of the order 5 GeV. We see from Fig. 1 that for a top quark not exceeding 200 GeV the upper bound of $m_H$ is 300(500) GeV at 95% (90%) confidence level. Fig. 2 shows that the central values of the world average $M_W$ and CDF $m_t$ are consistent with a Higgs scalar mass somewhat heavier than 1000 GeV to be contrasted to our output solution of the global fit. Even with the mass dependent QCD factor, we see that there is still 2.5 $\sigma$ deviation in $R(\Gamma_{b\bar{b}}/\Gamma_{had})$ from experiment irrespective to the uncertainty in $\alpha_s$ [5], which may be due to new physics beyond the SM.

In short, we find definite support for the evidence of the nonvanishing weak-loop correction from the current world average $M_W$ and LEP data. In particular, the CDF $m_t$ is a solution of the minimal $\chi^2$-fit to the current LEP data and the world average value of $M_W$ but with a Higgs $300 \pm 200$ GeV depending on the input value of $\alpha_s$. Thus, improved measurements of $M_W$ within 50 MeV accuracy in the future precision experiments can provide a crucial test of the SM as it will start to distinguish different Higgs mass to within 200 GeV.

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Figure Captions

Fig. 1 : The mass ranges of \( m_t \) and \( m_H \) from the minimal \( \chi^2 \)-fit to the 1994 LEP data and \( M_W = 80.23 \text{ GeV} \).

Fig. 2 : \( M_W \) versus \( m_t \) for fixed values of \( m_H \) from the full radiative correction in the standard model. The case of the minimal \( \chi^2 \)-fit to the 1994 LEP data with the full EWRC in Table 1 are indicated by \( \diamond \).