$R_b-R_c$ Crisis and the Higgs Boson Mass from LEP Precision Data

Jae Sik Lee and Jae Kwan Kim

Department of Physics,
Korea Advanced Institute of Science and Technology,
Taejon 305-701, Korea

ABSTRACT

We study the effects on the Higgs boson mass from LEP precision data of the new physics explaining $R_b-R_c$ crisis. We implement a fit to LEP observables with the new physics. We obtain $M_{H_{NewPhysics}} = 85^{+467}_{-56}$ GeV. Comparing with the value of the SM fit, $M_{H_{SM}} = 38^{+96}_{-21}$ GeV, the errors are larger and the central value is higher. The new physics may allow $M_H$ to have a value out of the range of $O(M_Z)$.

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1e-mail address: jslee@chep6.kaist.ac.kr
It is remarkable that the top-quark mass $M_t$ measured at CDF and D0 agrees well with the value predicted by the LEP precision data [1]. The success of the the $M_t$ prediction shifts the focus of interest to the prediction of the Higgs boson mass $M_H$ [2]. It is shown that there is a weak preference for a light Higgs boson mass $M_H < 300$ GeV. But it is not trivial that the electroweak data have consistently favored a Higgs mass in a range of $\mathcal{O}(M_Z)$ [3].

Recently it was reported by LEP collaborations that the measured ratios of $R_b \equiv \Gamma(Z \rightarrow bb)/\Gamma(Z \rightarrow \text{hadrons})$ and $R_c \equiv \Gamma(Z \rightarrow c\bar{c})/\Gamma(Z \rightarrow \text{hadrons})$ are different from those predicted by the standard model (SM). $R_b$ is higher than the SM prediction at 3.7 $\sigma$ level and $R_c$ is smaller than that at 2.7 $\sigma$ level [1]. These discrepancies may be the first signals for new physics beyond the SM if these are confirmed by future measurements.

A number of possible scenarios of new physics are being suggested to explain these $R_b$ and $R_c$ discrepancies simultaneously [4,5]. The nonuniversal interactions acting on only the b-quark and c-quark are attractive candidates for new physics explaining these discrepancies since the SM predictions for other flavors should not be disrupted by the new physics [6]. But it is not possible to explain $R_b$, $R_c$ with consistent $\alpha_s$ from low energy determinations invoking only non-standard $Zbb$– and $Zcc$–couplings.

With only nonuniversal interactions acting on the b-quark and c-quark results in $\alpha_s = 0.18$ [5]. This value is significantly conflict with the low energy determination $\alpha_s = 0.112 \pm 0.005$ [7]. If we don’t discount the measured value of $R_c$, therefore, new physics corrections to the $Zss$–couplings are also needed.

In this paper, we study the effects of the new physics which are introduced to explain $R_b$ and $R_c$ discrepancies on the Higgs boson mass prediction from the LEP precision data. By $\chi^2$ fitting to the LEP observables we calculate the new physics scale of the nonuniversal interactions and obtain $M_H$. There are theoretical bounds on the SM Higgs boson mass which are obtained from the stability of the electroweak vacuum [8] and by requiring the SM couplings to remain perturbative up to some scale [9]. We briefly comment whether our results of fitting are compatible with those from the vacuum stability and perturbativity.

In this paper we do not construct a specific model but use the effective Lagrangian
technique. We take the $Z \rightarrow f \bar{f}$ vertex to be given phenomenologically by the expression

$$\mathcal{L} \sim Z \mu \left[ \bar{f} \gamma_{\mu} (g_{V}^{eff,f} + g_{A}^{eff,f} \gamma_{5}) f \right],$$  

(1)

where $g_{V}^{eff,f}$ and $g_{A}^{eff,f}$ are the effective vector and axial vector coupling constants given by

$$g_{V}^{eff,f} = 2(g_{L}^{eff,f} + g_{R}^{eff,f}),$$

$$g_{A}^{eff,f} = 2(g_{L}^{eff,f} - g_{R}^{eff,f}).$$  

(2)

We introduce the nonuniversal interactions for $f = s, c, b$. For $f = c, b$, we parametrize the nonuniversal interaction effects in the $Z \rightarrow f \bar{f}$ vertex by introducing the parameters $\kappa_{L,R}^{f}$. These parameters shift the SM tree level couplings of the neutral currents $g_{L,R}^{f}$ to the effective couplings $g_{L,R}^{eff,f}$:

$$g_{L,R}^{eff,f} = g_{L,R}^{f}(1 + \kappa_{L,R}^{f}),$$  

(3)

where

$$g_{L}^{f} = I_{3}^{f} - Q^{f} \sin^{2} \theta_{W}, \quad g_{R}^{f} = -Q^{f} \sin^{2} \theta_{W}.$$  

(4)

$I_{3}^{f}$ and $Q^{f}$ are the weak isospin and electric charge respectively. Since non-standard couplings to the strange quark enter the neutral current observables only via their contributions to the total hadronic width of the $Z^{0}$ boson, $\Gamma_{had}$, we parametrize the effects by introducing the parameter $\delta \Gamma_{s}$. It is expected that the $\delta \Gamma_{s}$ is positive and has the value which nearly cancels the deficit of $\Gamma_{c}$ [7]. Since $(g_{L}^{f})^{2} \gg (g_{R}^{f})^{2}$, we fix $\kappa_{R}^{c,b} = 0$ in our analysis. So we introduced three parameters of new physics : $\kappa_{L}^{c}, \kappa_{L}^{b}$ and $\delta \Gamma_{s}$.

We use the following set of 15 variables in our fitting procedure (see Table 1) : $\Gamma_{Z}$, $\sigma_{tot}$, $R_{e} = \Gamma_{had}/\Gamma_{e}$, $R_{\mu} = \Gamma_{had}/\Gamma_{\mu}$, $R_{\tau} = \Gamma_{had}/\Gamma_{\tau}$, $A_{FB}^{0}(e)$, $A_{FB}^{0}(\mu)$, $A_{FB}^{0}(\tau)$, $A_{e}$, $R_{b}$, $R_{c}$, $A_{FB}^{0}(b)$, $A_{FB}^{0}(c)$ and $\sin^{2} \theta_{W}^{lep}$. From Table 1, we can see there are three observables which show deviations from the predictions of the SM : $A_{FB}^{0}(\tau)$, $R_{b}$ and $R_{c}$. The inability of the effective Lagrangian approach to fully explain the deviations in the asymmetry observables is discussed in Ref. [5]. And it is out of the range of this paper to consider $A_{FB}^{0}(\tau)$ deviation as the effect of the new physics. So we regard that this deviation results from not well understood systematic effects in the experiments.
We fix $\alpha_s = 0.123$ since the strong coupling constant is no longer strongly constrained by fits with the new physics [5]. We take another value of $\alpha_s = 0.112$ from low energy determinations to investigate the effects of the procedure of fixing $\alpha_s$ in our fit. We observe that the effects of varying $\alpha_s$ are negligible.

We used ZFITTER [10] with the function minimizing program MINUIT [11] to perform the $\chi^2$ fit for the LEP observables. Firstly, we implement the SM fit where no new physics parameters are added. And we fix $M_H = 300$ GeV to see the reliability for subsequent fits. In this case, the fitting parameters are $M_t$ and $\alpha_s$. We obtain

$$M_t = 171.5 \pm 8.4 \text{ GeV},$$
$$\alpha_s = 0.123 \pm 0.004.$$  

These values are well agree with those reported by the LEP electroweak working group [1]. Note the agreement of the fitted value of $M_t$ with the value measured at CDF and D0 : $180 \pm 12$ GeV (CDF + D0) [12].

Next, we implement the SM fit where no new physics parameters are added. In this case we fix $\alpha_s = 0.123$. Fixing $\alpha_s$ is for comparisons with the results from subsequent fits including new physics parameters. In this case, the fitting parameters are $M_t$ and $M_H$. We obtain

$$M_H = 38^{+96}_{-21} \text{ GeV} \left[ \log_{10}(M_H) = 1.53^{+0.60}_{-0.30} \right],$$
$$M_t = 145.3^{+16.7}_{-11.4}. $$

The lower and upper errors are obtained by projecting the $\Delta \chi^2 = 1$ ellipse in $(M_t, \log_{10}(M_H))$ plane on the vertical and horizontal axes. $M_t$ is lower than that of previous case mainly because we don’t fix $M_H$ at 300 GeV. These values are consistent with recent ones obtained by the authors of Ref. [3]. The results of this fit are shown in Table 1 as the SM results.

To investigate the effects of the new physics we perform the fit with the new physics parameters $\kappa_L^b$, $\kappa_L^c$ and $\delta\Gamma_s$ fixing $\alpha_s = 0.123$. This is our new physics fit. We obtain

$$M_H = 86^{+467}_{-56} \text{ GeV} \left[ \log_{10}(M_H) = 1.94^{+0.80}_{-0.47} \right],$$
$$M_t = 160.9^{+28.0}_{-14.0}. $$
\[
\kappa_L^b = 0.013 \pm 0.004, \\
\kappa_L^c = -0.059 \pm 0.026, \\
\delta \Gamma_s = 18.8 \pm 12.6 \text{ MeV.}
\]

As expected, \( \delta \Gamma_s \) has nearly the same value as the deficit of \( \Gamma_c \) and is positive. \( \kappa_L^c \) has negative value at 2 \( \sigma \) level. \( \kappa_L^b \) has the same central value of our previous work [6] at 3 \( \sigma \) level. \( M_t \) is more consistent with the value measured at CDF and D0 than the SM fit is. The errors of \( M_H \) are larger than those of the SM fit and the center value is higher. The upper limit at 2 \( \sigma \) level is about 2 TeV. This means that perturbative calculations are not reliable always. And the upper limit at 1 \( \sigma \) level (~ 500 GeV) diminishes the hope for finding the Higgs at the LEP2 or the LHC. In the SM framework, the electroweak data consistently favor a Higgs mass in a range of \( \mathcal{O}(M_Z) \). But, even though it is not significant because of the large error, there is a possibility that \( M_H \) has a value out of the range of \( \mathcal{O}(M_Z) \). The results of this fit are shown in Table 1 as the new physics.

To see the effects of future, more precise measurements of \( R_b \) and \( R_c \) on \( M_H \), we reduce errors of \( R_b \) and \( R_c \) by half. We do not change the central values of \( R_b \) and \( R_c \).

Fixing \( \alpha_s = 0.123 \), we obtain

\[
M_H = 85^{+278}_{-59} \text{ GeV} \left[ \log_{10}(M_H) = 1.93^{+0.63}_{-0.51} \right], \\
M_t = 160.9^{+19.7}_{-11.8}, \\
\kappa_L^b = 0.013 \pm 0.002, \\
\kappa_L^c = -0.063 \pm 0.014, \\
\delta \Gamma_s = 20.9 \pm 6.7 \text{ MeV.}
\]

We observe the errors of \( \kappa_L^b, \kappa_L^c, \) and \( \delta \Gamma_s \) decrease. The errors of \( M_H \) decrease slightly and the center value does not change.

To study the effects of fixing \( \alpha_s \), we also execute a fit fixing \( \alpha_s = 0.112 \). We obtain

\[
M_H = 86^{+474}_{-55} \text{ GeV} \left[ \log_{10}(M_H) = 1.94^{+0.81}_{-0.45} \right], \\
M_t = 160.9^{+27.8}_{-13.9}, \\
\kappa_L^b = 0.015 \pm 0.004,
\]

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\[ \kappa_L^c = -0.057 \pm 0.026, \]
\[ \delta \Gamma_s = 22.3 \pm 12.6 \text{ MeV}. \]

Comparing with the new physics fit, we can see the effects of fixing \( \alpha_s \) are negligible.

Because we take a model-independent approach, we do not explicitly describe the parameters \( \kappa_L^b, \kappa_L^c \) and \( \delta \Gamma_s \) by specific physical quantities here. We know, however, that these parameters are related to the new physics scale \( \Lambda \). For example, we consider the t-quark condensation models where the third generation \( Q_L \) and \( t_R \) states at a minimum participate in a new strong interaction for \( \kappa_L^b \) \[13\]. Then the relevant term of the effective Lagrangian is given by

\[ \mathcal{L}_{\text{eff}} \sim -\frac{1}{\Lambda^2} \bar{b} \gamma_\mu b \ell \gamma^\mu (g_V - g_A \gamma_5) t, \]

where \( g_V \) and \( g_A \) are parameters. Here one would expect that the t-quark loop will generate an effective contribution to \( Z \to \bar{b}b \) vertex \( \kappa_L^b \). Thus we have

\[ \kappa_L^b = \frac{g_A}{g_L^b} \frac{N_c}{8\pi^2} \frac{M_t^2}{\Lambda^2} \ln \left( \frac{\Lambda^2}{M_t^2} \right), \]

where \( N_c = 3 \). Our fit result \( \kappa_L^b = 0.013 \) yields \( \Lambda \sim 1 \text{ TeV} \) with \( |g_A| \sim 4\pi(0.11) \) \[14\].

The results from the analyses of stability \[8\] and perturbative \[9\] bounds on the SM Higgs boson mass gives

\[ \sim 50 \text{ GeV} < M_H < \sim 700 \text{ GeV} \quad \text{for } \Lambda = 1 \text{ TeV}. \]

The perturbative bound 700 GeV gets much corrections from two-loop \( \beta \) functions and one-loop matching condition on the Higgs boson mass. So this value is considered to be in a range from 500 GeV to 1 TeV. For smaller \( \Lambda \) the bounds become weaker. We can see that our new physics fit for \( M_H \) is well compatible with these bounds.

We implement a fit to LEP observables with new physics explaining \( R_b \) and \( R_c \) discrepancies. We obtain \( M_H^{\text{NewPhysics}} = 85^{+467}_{-56} \) GeV. Comparing with the value of the SM fit, \( M_H^{\text{SM}} = 38^{+96}_{-21} \) GeV, the errors are larger and the central value is higher. The new physics may allow \( M_H \) to have a value out of the range of \( \mathcal{O}(M_Z) \).

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**Table Captions**

Table 1: Our global fit to LEP observables in the standard model framework and with nonuniversal interactions explaining $R_b$ and $R_c$ discrepancies.
| Observables | Experiment | SM results | $\chi^2$ | New Physics | $\chi^2$ |
|-------------|------------|------------|----------|-------------|----------|
| $\Gamma_Z$(GeV) | 2.4963 ± 0.0032 | 2.4936 | 0.710 | 2.4963 | 0.000 |
| $\sigma_{tot}$(nb) | 41.488 ± 0.078 | 41.429 | 0.580 | 41.441 | 0.368 |
| $R_e$ | 20.797 ± 0.058 | 20.799 | 0.001 | 20.784 | 0.052 |
| $R_\mu$ | 20.796 ± 0.043 | 20.799 | 0.004 | 20.784 | 0.079 |
| $R_\tau$ | 20.813 ± 0.061 | 20.846 | 0.290 | 20.831 | 0.087 |
| $A^0_{FB}(e)$ | 0.0157 ± 0.0028 | 0.0157 | 0.000 | 0.0158 | 0.001 |
| $A^0_{FB}(\mu)$ | 0.0163 ± 0.0016 | 0.0157 | 0.134 | 0.0158 | 0.103 |
| $A^0_{FB}(\tau)$ | 0.0206 ± 0.0023 | 0.0157 | 4.513 | 0.0158 | 4.381 |
| $A_\tau$ | 0.1418 ± 0.0075 | 0.1447 | 0.155 | 0.1451 | 0.191 |
| $A_e$ | 0.139 ± 0.0089 | 0.1447 | 0.417 | 0.1451 | 0.466 |
| $R_b$ | 0.2219 ± 0.0017 | 0.2168 | 8.868 | 0.2219 | 0.000 |
| $R_c$ | 0.154 ± 0.0074 | 0.1719 | 5.863 | 0.1557 | 0.053 |
| $A^0_{FB}(b)$ | 0.0997 ± 0.0031 | 0.1016 | 0.361 | 0.1020 | 0.535 |
| $A^0_{FB}(c)$ | 0.0729 ± 0.0058 | 0.0725 | 0.006 | 0.0688 | 0.494 |
| $\sin^2\theta_W$ | 0.2320 ± 0.0016 | 0.2318 | 0.014 | 0.2318 | 0.021 |
| total | | 21.9 | | 6.8 | |

Table 1: