Implications of the recent CERN LEP data on nonuniversal interactions with the precision electroweak tests

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Abstract

We explore the nonuniversal interaction effects in terms of the precision variables epsilons with the recent LEP data reported by the Electroweak Working Group. The epsilon variables with the nonuniversal interactions are calculated and constrained by the experimental ellipses in the $\epsilon_1-\epsilon_b$, $\epsilon_2-\epsilon_b$, and $\epsilon_3-\epsilon_b$ planes. We find that the new data enables us to make a stringent test on the correction to $Z \rightarrow b\bar{b}$ vertex. The $\epsilon_b$ variable is sensitive to the $Zb\bar{b}$ couplings and thus plays a major role to give constraints on the nonuniversal interaction effects. Upon imposing the new data on $\epsilon_b$, we have the allowed range of the model parameter $\kappa_L = 0.0063 \pm 0.0030$ at 1-σ level with $m_t = 175$ GeV. Along with the minimal contact term, we predict the new physics scale $\Lambda \sim 1.6$ TeV. By combining the experimental results from all planes we obtain

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the allowed range of $\kappa_L : 0.003 < \kappa_L < 0.010$ at 95 \% C.L.
Since the top quark was observed and its mass has been measured from the Fermilab \( p\bar{p} \) collider Tevatron, the influence of the large value of the top quark mass on the \( Z \rightarrow b\bar{b} \) vertex is drawing much attention. In the year of 1995, the value of \( R_b \equiv \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons}) \) was reported to be actually more than three standard deviations higher from the Standard Model (SM) prediction with the heavy top and it stimulated many theoretical and experimental efforts. The most recent data from ALEPH [1], DELPHI [2], OPAL [3] and SLD [4], however, come closer to the SM prediction. Following the LEP electroweak working group report [5], the average of 1996 data (LEP+SLC) is \( R_b = 0.2178 \pm 0.0011 \), which is about 1.8 standard deviations higher than the SM prediction. In spite of the experimental improvement of the situation, much interest is taken in the \( R_b \) problem as ever since the discrepancy between the measured value and the SM predicted value still exists. Furthermore recent data have different systematics from those obtained until 1995 and it is not clear whether it is appropriate to discard old measurements from the world average. Therefore it is still interesting to consider the possibility of the new physics beyond the SM which affect the \( Z \rightarrow b\bar{b} \) vertex.

The nonuniversal interaction acting only on the third generation can be an attractive candidate for the new physics, at least in the viewpoint of the effective theory, since we favor that the SM predictions for other flavours should not be much disrupted by the new physics. Such models are mainly motivated by the idea that mass of the top quark turns out to be of order of the weak scale and so the top quark could be responsible for the electroweak symmetry breaking. The top quark condensation may be formed if we introduce a new gauge interaction and the bound state \( \langle \bar{t}t \rangle \) would play the role of the Goldstone bosons for the electroweak symmetry breaking instead of the elementary scalar.

In this paper we attempt to constrain the nonuniversal interactions in terms of the precision variables \( \epsilon \)'s. We consider the general approach to introduce the nonuniversal corrections to the \( Z \rightarrow b\bar{b} \) vertex in a model independent way. Since the anomalous nonuniversal interaction terms should be \( \text{SU}(2)_L \times \text{U}(1)_Y \) invariant, \( b \)-quark also interacts with \( t \)-quark via involving the left–handed doublet interactions. This anomalous interaction results in the
additional contributions to the $Z \to b\bar{b}$ vertex. We parametrize the nonuniversal interaction effects in the $Z \to b\bar{b}$ vertex by the shift of the tree level SM couplings of the neutral currents $g_{L,R}$. We let the effective couplings $g_{L,R}^{\text{eff}}$:

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

where

$$g_L = -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W, \quad g_R = \frac{1}{3} \sin^2 \theta_W .$$

In order to parametrize the new physics effects, we use the precision variables $\epsilon_i$'s introduced by Altarelli et al. [7] here. We calculated the epsilons for the updated analysis of the precision electroweak tests of the supergravity models by taking into account the new LEP data presented at the 28th ICHEP (1996, Poland) to obtain more accurate experimental values of $\epsilon_{1,2,3,b}$ in the ref. [8]. Out of the epsilon variables, $\epsilon_b$ has been of particular interest because it encodes the loop corrections to the $Z \to b\bar{b}$ vertex and is relevant for our aim.

Our new physics corrections $\kappa_{L,R}$ are generically due to the sum of the bubble diagram of the top quark in this type of model. We calculate $\epsilon_{1,2,3,b}$ with nonuniversal corrections and constrain them by the results of the experimental data.

In the original work [9], the variables $\epsilon_1$, $\epsilon_2$ and $\epsilon_3$ were defined from the basic observables, the mass ratio of $W$ and $Z$ bosons $m_W/m_Z$, the leptonic width $\Gamma_l$ and the forward–backward asymmetry for charged leptons $A_{FB}^l$. These observables are all defined at the $Z$–peak, precisely measured and free from important hadronic effects like $\alpha_s(m_Z)$ or the $Z \to b\bar{b}$ vertex. In terms of these observables, $\epsilon_1$, $\epsilon_2$ and $\epsilon_3$, we have the virtue that the most interesting physical results are already obtained at a completely model independent level without assumptions like the dominance of vacuum polarisation diagrams.

Because of the large $m_t$–dependent SM corrections to the $Z \to b\bar{b}$ vertex, however, the $\epsilon_i$'s and $\Gamma_b$ can only be correlated for a given value of $m_t$. In order to overcome this limitation, Altarelli et al. [7] added a new parameter, $\epsilon_b$, which encodes the $m_t$–dependent corrections to $Z \to b\bar{b}$ vertex and slightly modified other $\epsilon_i$'s. Hence the four $\epsilon_i$'s are defined from an
enlarged set of basic observables $m_W/m_Z$, $\Gamma_l$, $A_{FB}$ and $\Gamma_b$ without need of specifying $m_t$. Consequently the $m_t$–dependence for all observables via loops come out through the $\epsilon_i$'s. We work with this extended scheme here because we are interested in the corrections to $Z \rightarrow b\bar{b}$ vertex.

Since the nonuniversal corrections affect only on the $Z \rightarrow b\bar{b}$ vertex among the basic observables, we focus on the variable $\epsilon_b$ here. The correction to $g_R$ does not affect $\Gamma_b$ significantly because $g_L \gg g_R$ in eq. (1), and we neglect the effect of $\kappa_R$ hereafter. We calculate the epsilon variables with the nonuniversal corrections using the ZFITTER [8]. Fig. 1 shows the $\kappa_L$–dependence of the $\epsilon_b$ variable for $m_t = 175$ GeV. We know that $\epsilon_b$ is insensitive to the variation of the Higgs mass $m_H$. The range of $\kappa_L$ corresponding to the 1-$\sigma$ of the experimental data is given by

$$\kappa_L = 0.0033 \sim 0.0093 \ .$$

(2)

The epsilon variables are obtained in the ref. [8] from the recent LEP data given in table I reported by the LEP Electroweak Working Group [5]:

$$\epsilon_1 = (4.0 \pm 1.2) \times 10^{-3}$$

$$\epsilon_2 = (-4.3 \pm 1.7) \times 10^{-3}$$

$$\epsilon_3 = (2.3 \pm 1.7) \times 10^{-3}$$

$$\epsilon_b = (-1.5 \pm 2.5) \times 10^{-3} \ .$$

(3)

Note that the lepton universality assumption is assumed for the values of $\Gamma_l$ and $A_{FB}$. Besides in the $\epsilon_1 - \epsilon_b$ plane, we attempt to constrain the model by the experimental ellipses in the $\epsilon_2 - \epsilon_b$ and $\epsilon_3 - \epsilon_b$ planes here. In Fig. 2, the experimental ellipses for 1-$\sigma$ level and 90%, 95% confidence level are given in the $\epsilon_1 - \epsilon_b$ plane (a), in the $\epsilon_2 - \epsilon_b$ plane (b) and in the $\epsilon_3 - \epsilon_b$ plane (c) with our model predictions for varying the parameter $\kappa_L$ and the Higgs mass $m_H$. We find the SM results ($\kappa_L = 0$) deviate even from the 95 % C.L. ellipses for all of three cases and that the nonuniversal corrections improve the situations in general. $\epsilon_1$ and $\epsilon_2$ favor the heavy Higgs and $\epsilon_3$ favors the light Higgs mass $\sim 100$ GeV. As the more precise value of
the W boson mass is reported, $\epsilon_2$ variable can also provide a stringent test for the theoretical predictions. Here, we used the value of the W boson mass fitted to LEP data alone by LEP Electroweak Working Group [3]. As its precise measurement will be performed at LEP II, we can expect the progress in $\epsilon_2$ analysis. We find that $\epsilon_3$ demands the new physics most strongly among them and that the Higgs mass get the upper bound $m_H \lesssim 300$ GeV at 95 % C. L.. Combining the experimental ellipses conditions on the $\epsilon_1-\epsilon_b$, $\epsilon_2-\epsilon_b$, and $\epsilon_3-\epsilon_b$ planes, we obtained the range of allowed values of $\kappa_L : 0.003 < \kappa_L < 0.010$ at 95 % C. L. with the Higgs mass $m_H = 100 \sim 300$ GeV. The heavier the Higgs, the narrower the allowed region. At 90 % C.L., we obtain extremely small region : $\kappa_L \sim 0.007$ and $m_H \sim 120$ GeV. In our analysis, we use the values $\alpha_s(m_Z) = 0.118$ and $\alpha(m_Z) = 1/128.87$.

The mass of the top quark is being measured more precisely by the CDF and D0 collaborations at Tevatron. As stated before, we use 175 GeV as input value of $m_t$ in Fig. 1 and Fig. 2, which is the central value of the recent CDF and D0 report [4]. The $Z \to b\bar{b}$ vertex is, however, affected much by the change of $m_t$ and we present the $m_t$-dependence of $\epsilon_b$ in Fig. 3. The value of $m_t$ is varied from 170 to 180 GeV. If $m_t = 170$ GeV, the allowed range of $\kappa_L$ is given by $\kappa_L = 0.0032 \sim 0.0088$ and if $m_t = 180$ GeV, $\kappa_L = 0.0039 \sim 0.0099$ at 1-$\sigma$ level. We find that the value of $\epsilon_b$ is not significantly changed in this range of $m_t$. The major features of the constraints from $\epsilon_{1,2,3,b}$ for the nonuniversal interactions are summarized in table II.

In this work we explored the nonuniversal interaction effects on the $Z \to b\bar{b}$ vertex in terms of the $\epsilon$ variables using the recent experimental data. We did not explicitly describe the parameter $\kappa_L$ by specific physical quantity here since we take a model-independent approach. Various models which can give the effective Lagrangian for the $Z \to b\bar{b}$ vertex

$$\mathcal{L}_{eff} \sim Z^n(b\gamma_\mu(g^{eff}_V g^{eff}_A \gamma_5)b)$$

have been considered by several authors [11–14]. One of the most appropriate type of models is the top condensation idea in which the third generation has their own gauge interaction. In general we have the several contact terms which are $d > 4$ at a high energy scale in those
models. We find a general list of contact terms in ref. 15,16. As the minimal contents of the model, left–handed SU(2) doublet for the third generation and the right–handed singlet \( t_R \) are coupled in a new gauge interaction. We can write a relevant term of the effective Lagrangian as

\[ L_{\text{eff}} = -\frac{1}{\Lambda^2} \bar{b}\gamma_\mu b\bar{\gamma}_\mu (g_V - g_A \gamma_5) t + \ldots \]  

(5)

where \( g_V, g_A \) are model parameters. Then the effective contribution to \( Z \to b\bar{b} \) vertex, \( \kappa_L \), is generated via the top quark loops thus we obtain the relation,

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

(6)

The central value from the experimental data \( \epsilon_b = -1.5 \) leads to the value of parameter \( \kappa_L \sim 0.0063 \) and yields the new physics scale \( \Lambda \sim 1.6 \) TeV. We find that the new physics scale is rather low and it enables us to avoid the extra fine–tuning of the new gauge couplings for the hierarchy between \( m_t \) and \( \Lambda \). On the other hand, such a four fermion interaction is not enough for the electroweak symmetry breaking. Hill suggested a model in which an separate mechanism like extended technicolor is involved to account for the observed \( W \) and \( Z \) masses 17. Our analysis is applicable to that model because we pay our attention to only the influences on the \( Z \to b\bar{b} \) vertex. With \( \kappa_L = 0.0063 \) corresponding to the central value from data, we calculate the \( R_b = 0.2175 \), which agrees with the experimental results from LEP and SLC, as we expected. For the \( R_b \) from LEP data, we obtain the range of \( \kappa_L \):

\[ \kappa_L = 0.0038 \sim 0.0110 . \]  

(7)

at 1-\( \sigma \) level, of which the values are slightly larger than those from the \( \epsilon_b \).

In conclusion, we presented an analysis for the extension of the SM with the nonuniversal interactions in terms of the precision variables \( \epsilon \)’s. As a result of the better accuracy of the precision test with new data from the LEP, the study of the epsilon varibles provide positive hints for new physics beyond the SM and the nonuniversal interactions, at least as an effective theory, could be a good candidate for the new physics.
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TABLES

TABLE I. The LEP data reported by the LEP Electroweak Working Group at the 28th ICHEP (1996, Poland).

| Parameter | Value                  |
|-----------|------------------------|
| $M_W$     | $80.2780 \pm 0.0490$ GeV |
| $M_Z$     | $91.1863 \pm 0.0020$ GeV |
| $\Gamma_l$ | $83.91 \pm 0.11$ MeV  |
| $A_{FB}^l$ | $0.0174 \pm 0.0010$    |
| $\Gamma_b$ | $379.9 \pm 2.2$ MeV   |
TABLE II. The major features of the constraints from $\epsilon_b$ and all ellipses in $\epsilon_1-\epsilon_b$, $\epsilon_2-\epsilon_b$, and $\epsilon_3-\epsilon_b$ planes. for the nonuniversal correction to $Z \to b\bar{b}$ vertex.

| $m_t$  | $\epsilon_b$ constraints | combined ellipses constraints |
|-------|--------------------------|-------------------------------|
| 170 GeV | $\kappa_L = 0.0028 \sim 0.0088$ | $0.004 < \kappa_L < 0.010$ at 95 % C. L. when $m_H \sim 100$ GeV |
|       |                          | $0.003 < \kappa_L < 0.009$ at 95 % C. L. when $m_H \sim 200$ GeV |
| 175 GeV | $\kappa_L = 0.0033 \sim 0.0093$ | $0.004 < \kappa_L < 0.008$ at 95 % C. L. when $m_H \sim 300$ GeV |
|       |                          | excluded when $m_H > 300$ GeV |
|       |                          | $\kappa_L \sim 0.007$, $m_H \sim 120$ GeV at 90 % C. L. |
| 180 GeV | $\kappa_L = 0.0039 \sim 0.0099$ | at 1–σ level |

at 1–σ level
Figure Captions

Fig. 1
Plot of $\epsilon_b$ in units of $10^{-3}$ as a function of the parameter $\kappa_L$ with varying the Higgs mass $m_H$. The 1-$\sigma$ range obtained from the LEP data is also shown.

Fig. 2
Plot of the model predictions in units of $10^{-3}$ with varying the model parameter $\kappa_L$ and the Higgs mass $m_H$ in (a) $\epsilon_1-\epsilon_b$ plane, (b) $\epsilon_2-\epsilon_b$ plane and (c) $\epsilon_3-\epsilon_b$ plane. The experimental ellipses at 1-$\sigma$, 90 % C.L. and 95 % C.L. are also shown.

Fig. 3
Plot of the $m_t$-dependence of the $\epsilon_b$ variable in units of $10^{-3}$ with varying $\kappa_L$ values. The 1-$\sigma$ range obtained from the LEP data is denoted by the dashed line.
Fig. 1
Fig. 2 (a)

$m_s = 175 \text{ GeV}$

$m_H = 100 - 1000 \text{ GeV}$

(from right to left)
$\kappa_L = 0.012$

$\kappa_L = 0.010$

$\kappa_L = 0.008$

$\kappa_L = 0.006$

$\kappa_L = 0.004$

$\kappa_L = 0.002$

$\kappa_L = 0.000$

$m_{\tau} = 175$ GeV

$m_{H} = 100 - 1000$ GeV

(from left to right)

Fig. 2 (b)
Fig. 2 (c)

\( m_t = 175 \, \text{GeV} \)

\( m_W = 100 - 1000 \, \text{GeV} \)

(from left to right)
