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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 ϵ_1–ϵ_b, ϵ_2–ϵ_b, and ϵ_3–ϵ_b planes. We find that the new data enables us to make a stringent test on the correction to $Z \to b\bar{b}$ vertex. The ϵ_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 ϵ_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 κ_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 $Z \to b\bar{b}$ vertex is drawing much attention. In the year of 1995, the value of $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ 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 systamatics 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 $Z \to b\bar{b}$ 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 ϵ's. We consider the general approach to introduce the nonuniversal corrections to the $Z \to b\bar{b}$ vertex in a model independent way. Since the anomalous nonuniversal interaction terms should be $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ 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 $g^{\rm eff}_{L,R}$:

$$g^{\rm eff}_{L,R} = g_{L,R}(1 + \kappa_{L,R}) \quad , \tag{1}$$

where

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

In order to parametrize the new physics effects, we use the precision variables ϵ_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, ϵ_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 ϵ_1, ϵ_2 and ϵ_3 were defined from the basic observables, the mass ratio of W and Z bosons m_W/m_Z, the leptonic width Γ_l and the forward–backward asymmetry for charged leptons A^l_{FB}. 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, ϵ_1, ϵ_2 and ϵ_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 ϵ_i's and Γ_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, ϵ_b, which encodes the m_t–dependent corrections to $Z \to b\bar{b}$ vertex and slightly modified other ϵ_i's. Hence the four ϵ_i's are defined from an enlarged set of basic observables m_W/m_Z, Γ_l, A^l_{FB} and Γ_b without need of specifying m_t. Consequently the m_t–dependence for all observables via loops come out through the ϵ_i's. We work with this extended scheme here because we are interested in the corrections to $Z \to b\bar{b}$ vertex.

Since the nonuniversal corrections affect only on the $Z \to b\bar{b}$ vertex among the basic observables, we focus on the variable ϵ_b here. The correction to g_R does not affect Γ_b significantly because $g_L \gg g_R$ in eq. (1), and we neglect the effect of κ_R hereafter. We calculate the epsilon variables with the nonuniversal corrections using the ZFITTER [6]. Fig. 1 shows the κ_L–dependence of the ϵ_b variable for $m_t = 175$ GeV. We know that ϵ_b is insensitive to the variation of the Higgs mass m_H. The range of κ_L corresponding to the 1-σ of the experimental data is given by

$$\kappa_L = 0.0033 \sim 0.0093 \quad . \tag{2}$$

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]:

$$\begin{aligned} \epsilon_1 &= (4.0 \pm 1.2) \times 10^{-3} \\ \epsilon_2 &= (-4.3 \pm 1.7) \times 10^{-3} \\ \epsilon_3 &= (2.3 \pm 1.7) \times 10^{-3} \\ \epsilon_b &= (-1.5 \pm 2.5) \times 10^{-3} \quad . \end{aligned} \tag{3}$$

Note that the lepton universality assumption is assumed for the values of Γ_l and A^l_{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-σ 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 κ_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. ϵ_1 and ϵ_2 favor the heavy Higgs and ϵ_3 favors the light Higgs mass $\sim$ 100 GeV. As the more precise value of the W boson mass is reported, ϵ_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 [5]. As its precise measurement will be performed at LEP II, we can expect the progress in ϵ_2 analysis. We find that ϵ_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 ϵ_1–ϵ_b, ϵ_2–ϵ_b, and ϵ_3–ϵ_b planes, we obtained the range of allowed values of κ_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 aloowed 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 [10]. 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 ϵ_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 κ_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-σ level. We find that the value of ϵ_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 ϵ variables using the recent experimental data. We did not explicitly describe the parameter κ_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

$$\mathcal{L}_{eff} \sim Z^\mu(\bar{b}\gamma_\mu(g_V^{eff} + g_A^{eff}\gamma_5)b) \tag{4}$$

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

$$\mathcal{L}_{eff} = -\frac{1}{\Lambda^2}\bar{b}\gamma_\mu b\bar{t}\gamma^\mu(g_V - g_A\gamma_5)t + ... \tag{5}$$

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

$$\kappa_L = \frac{g_A}{g_L}\frac{N_c}{8\pi^2}\frac{m_t^2}{\Lambda^2}\ln\left(\frac{\Lambda^2}{m_t^2}\right) \quad . \tag{6}$$

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 Λ. 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 κ_L:

$$\kappa_L = 0.0038 \sim 0.0110 \quad . \tag{7}$$

at 1-σ level, of which the values are slightly larger than those from the ϵ_b.

In conclusion, we presented an analysis for the extension of the SM with the nonuniversal interactions in terms of the precision variables ϵ'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).

M_W	80.2780 ± 0.0490 GeV
M_Z	91.1863 ± 0.0020 GeV
Γ_l	83.91 ± 0.11 MeV
A^l_{FB}	0.0174 ± 0.0010
Γ_b	379.9 ± 2.2 MeV

TABLE II. The major features of the constraints from ϵ_b and all ellipses in ϵ_1–ϵ_b, ϵ_2–ϵ_b, and ϵ_3–ϵ_b planes. for the nonuniversal correction to $Z \to b\bar{b}$ vertex.

m_t	ϵ_b constraints	combined ellipses constraints
170 GeV	$\kappa_L = 0.0028 \sim 0.0088$ at 1–σ level	
175 GeV	$\kappa_L = 0.0033 \sim 0.0093$ at 1–σ level	$0.004 < \kappa_L < 0.010$ 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 $0.004 < \kappa_L < 0.008$ 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	

Figure Captions

Fig. 1

Plot of ϵ_b in units of 10^{-3} as a function of the parameter κ_L with varying the Higgs mass m_H. The 1-σ 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 κ_L and the Higgs mass m_H in (a) ϵ_1–ϵ_b plane, (b) ϵ_2–ϵ_b plane and (c) ϵ_3–ϵ_b plane. The experimental ellipses at 1-σ, 90 % C.L. and 95 % C.L. are also shown.

Fig. 3

Plot of the m_t–dependence of the ϵ_b variable in units of 10^{-3} with varying κ_L values. The 1-σ range obtained from the LEP data is denoted by the dashed line.

FIGURES

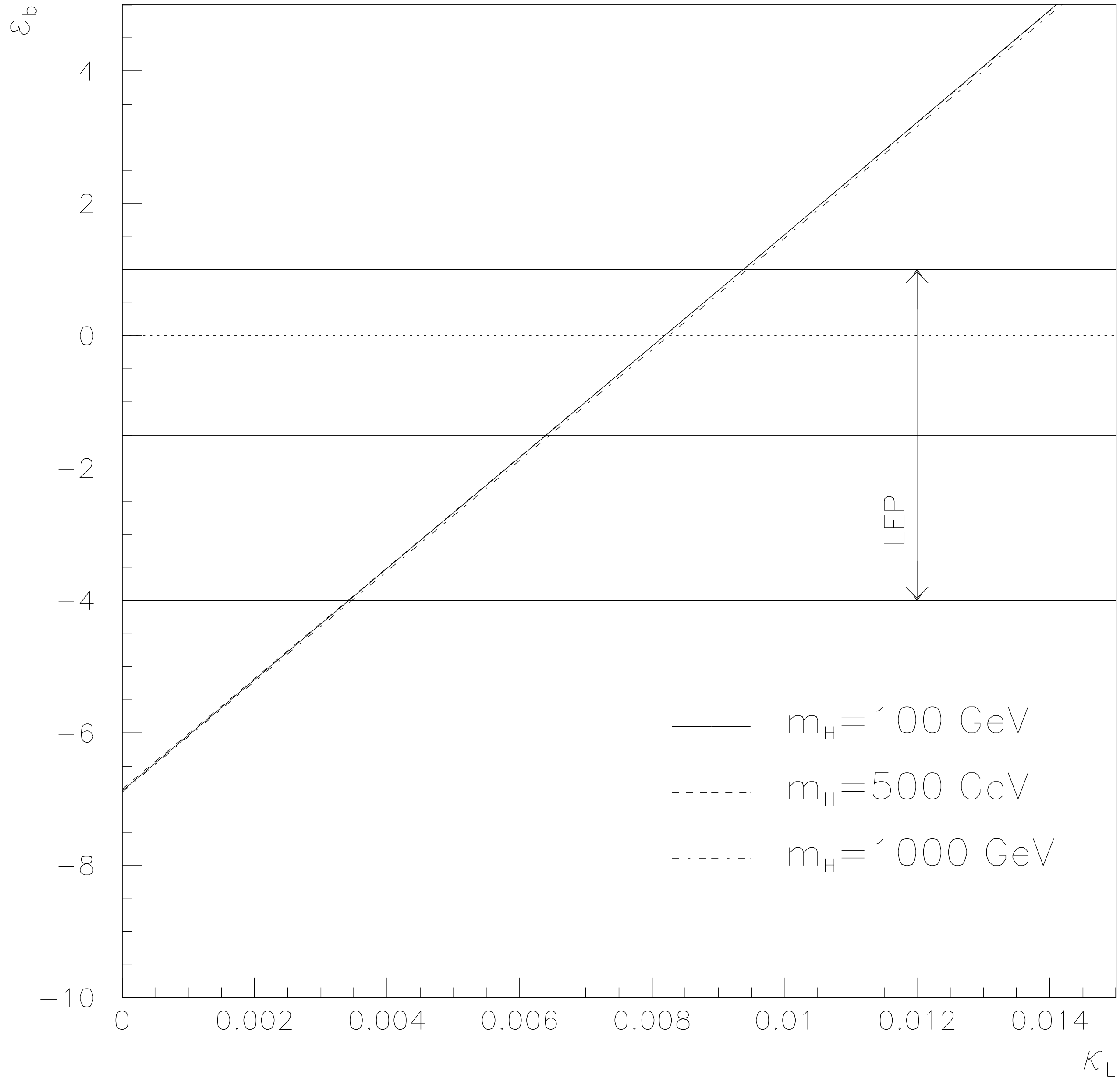


Fig. 1

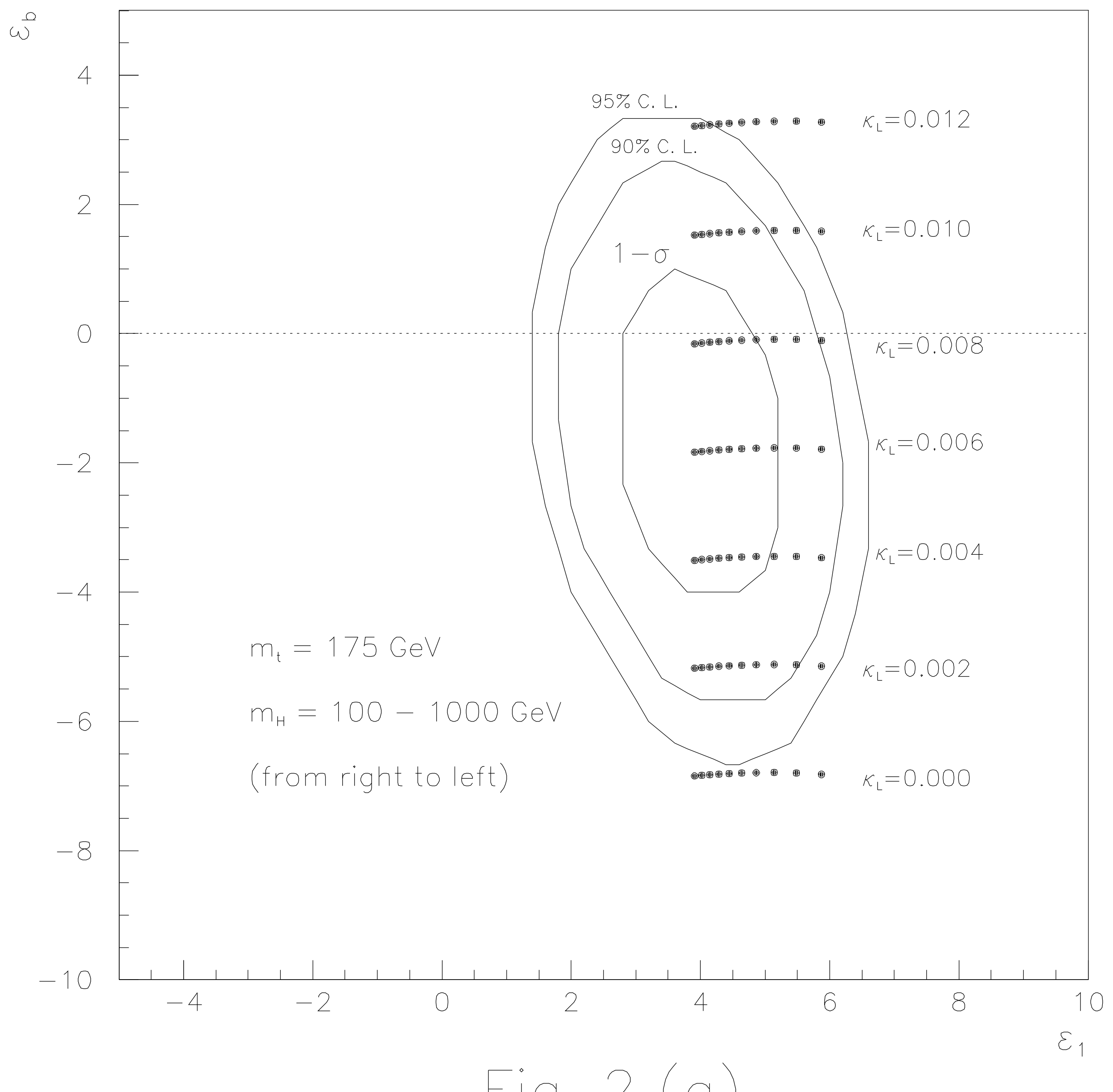

ε_b
4
2
0
−2
−4
−6
−8
−10
−4
−2
0
2
4
6
8
10
ε_1
95% C. L.
90% C. L.
$1-\sigma$
κ_L=0.012
κ_L=0.010
κ_L=0.008
κ_L=0.006
κ_L=0.004
κ_L=0.002
κ_L=0.000
m_t = 175 GeV
m_H = 100 − 1000 GeV
(from right to left)

Fig. 2 (a)

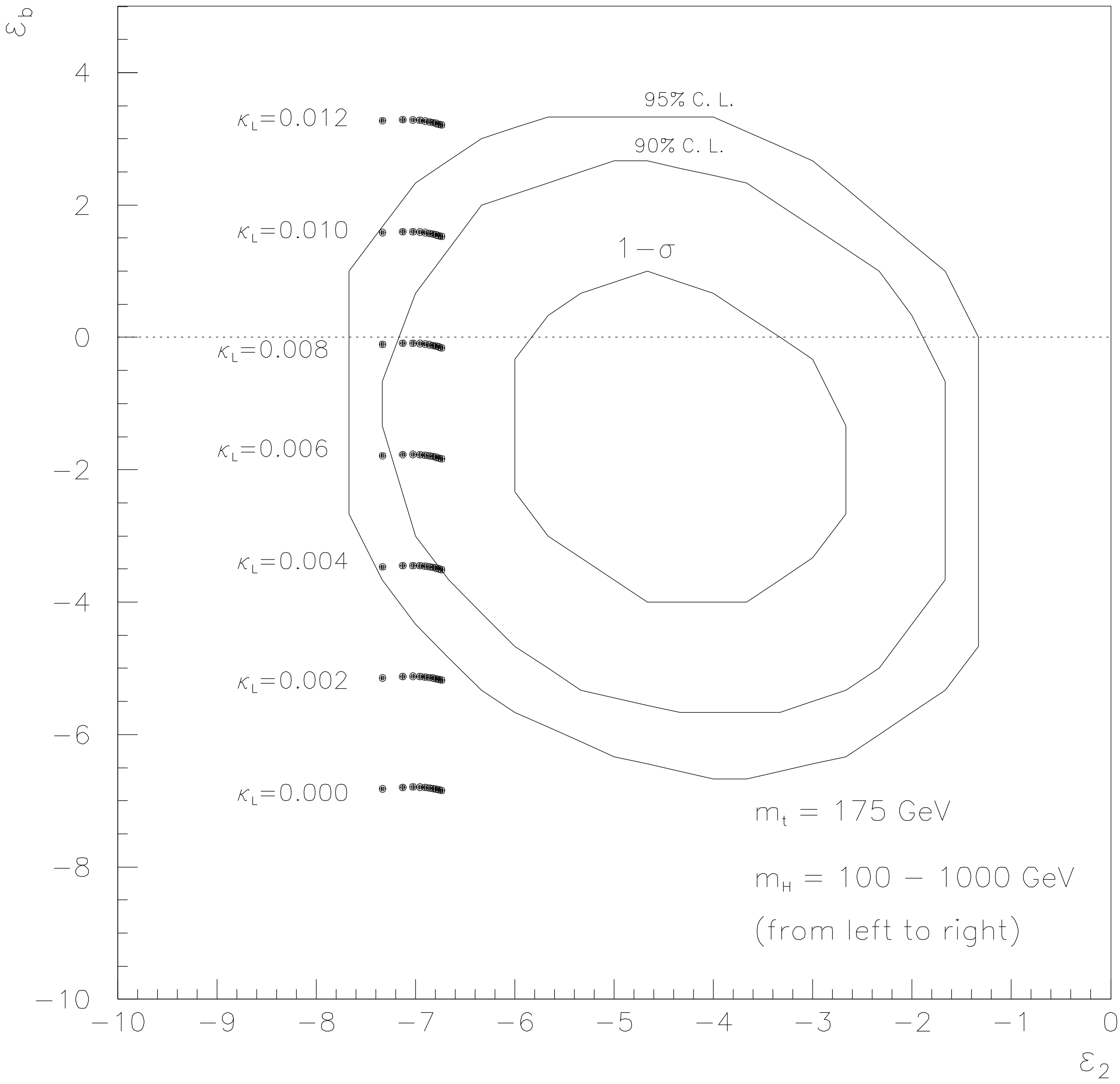
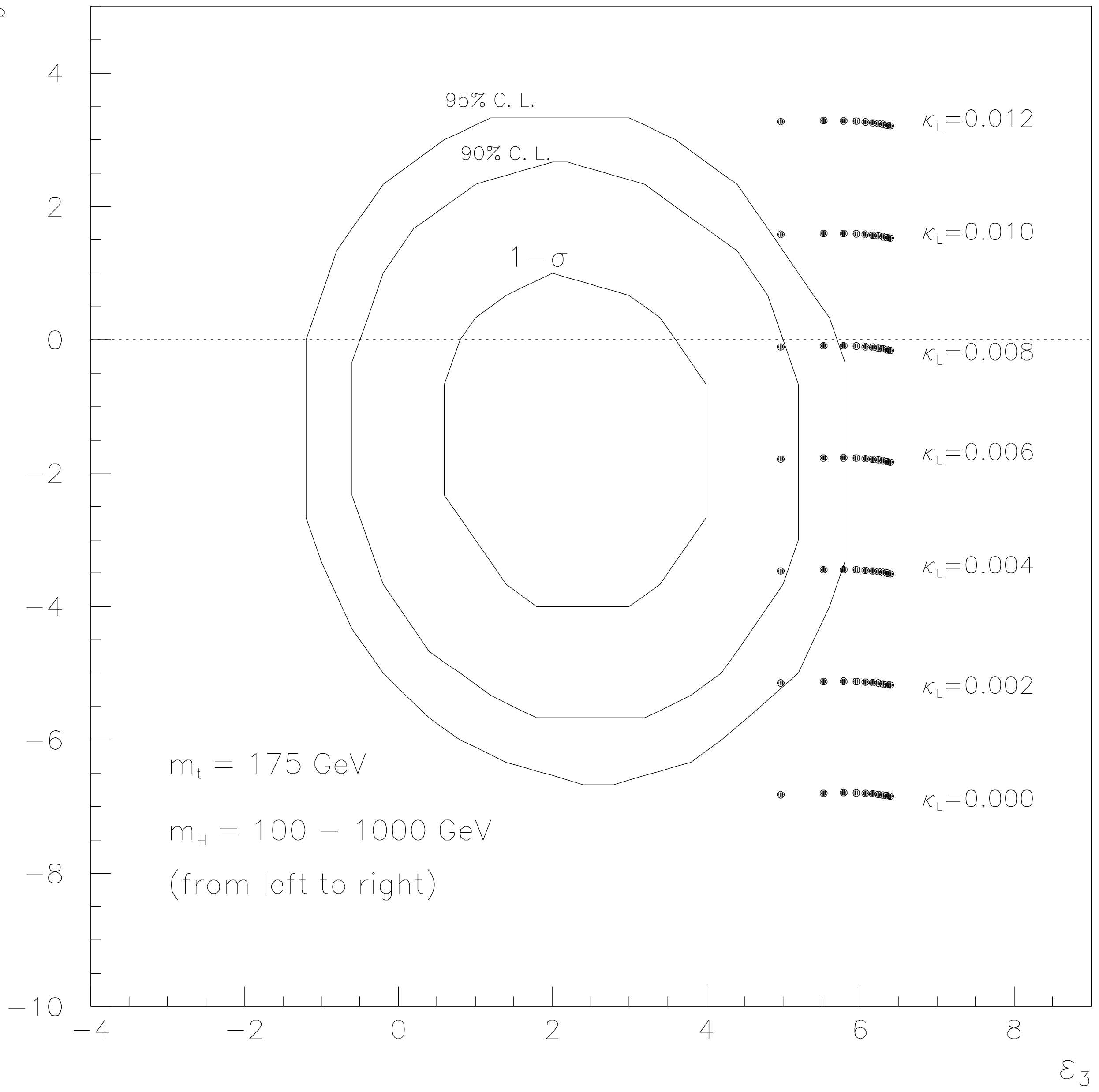

ε_b
ε_2
4
2
0
−2
−4
−6
−8
−10
−10
−9
−8
−7
−6
−5
−4
−3
−2
−1
0
95% C. L.
90% C. L.
$1-\sigma$
κ_L=0.012
κ_L=0.010
κ_L=0.008
κ_L=0.006
κ_L=0.004
κ_L=0.002
κ_L=0.000
m_t = 175 GeV
m_H = 100 − 1000 GeV
(from left to right)

Fig. 2 (b)



ε_b
ε_3
95% C. L.
90% C. L.
$1-\sigma$
$\kappa_L=0.012$
$\kappa_L=0.010$
$\kappa_L=0.008$
$\kappa_L=0.006$
$\kappa_L=0.004$
$\kappa_L=0.002$
$\kappa_L=0.000$
m_t = 175 GeV
m_H = 100 − 1000 GeV
(from left to right)
4
2
0
−2
−4
−6
−8
−10
−4
−2
0
2
4
6
8

Fig. 2 (c)

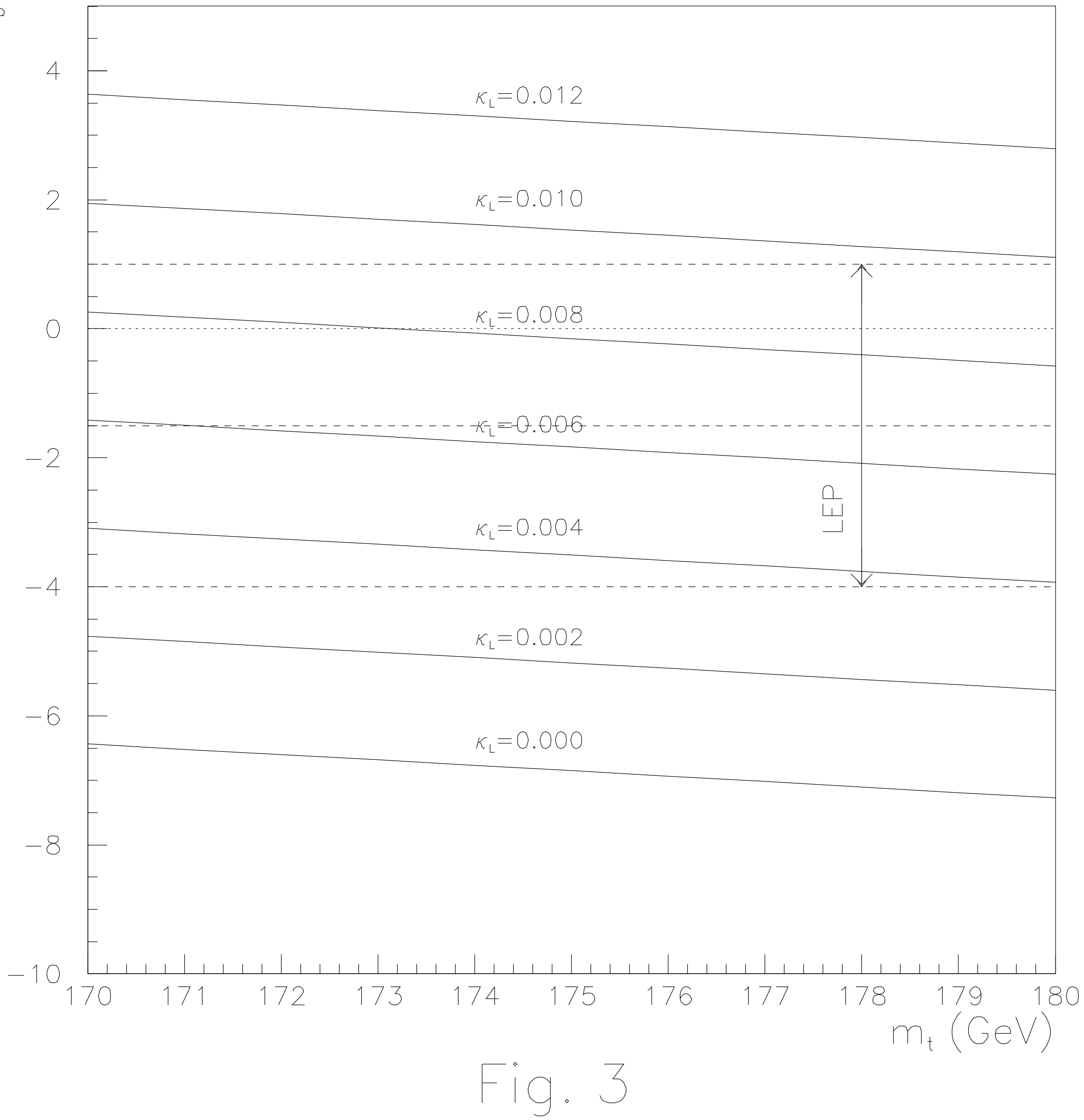

ε_b
4
2
0
−2
−4
−6
−8
−10
170
171
172
173
174
175
176
177
178
179
180
m_t (GeV)
κ_L=0.012
κ_L=0.010
κ_L=0.008
κ_L=0.006
κ_L=0.004
κ_L=0.002
κ_L=0.000
LEP

Fig. 3