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Inclusion of $Z \to b\bar{b}$ vertex corrections in Precision Electroweak Tests on the $Sp(6)_L \times U(1)_Y$ Model

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Abstract

We extend our previous work on the precision electroweak tests in the $Sp(6)_L \times U(1)_Y$ family model to include for the first time the important $Z \to b\bar{b}$ vertex corrections encoded in a new variable ϵ_b, utilizing all the latest LEP data. We include in our analysis the one loop EW radiative corrections due to the new bosons in terms of $\epsilon_{1,b}$ and $\Delta\Gamma_Z$. We find that the correlation between ϵ_1 and ϵ_b makes the combined constraint much stronger than the individual ones. The model is consistent with the recent CDF result of $m_t = 174 \pm 10^{+13}_{-12}$ GeV, but it can not accomodate $m_t \gtrsim 195$ GeV.

1 Introduction

Having unknown top quark mass(m_t) has long been one of the biggest disadvantage in studying the Standard Model(SM) and its extensions. With the very recent announcement of CDF collaboration at Tevatron on their evidence for top quark production[1] with $m_t = 174 \pm 10^{+13}_{-12}$ GeV, there are amusing possibilities that one can constrain further possible new physics beyond the SM from the precision LEP data. Precision measurements at the LEP have been remarkably successful in confirming the validity of the SM[2]. Indeed, in order to have agreements between theory and experiments, one has to go beyond the tree-level calculations and include known electroweak(EW) radiative corrections. However, from the theoretical point of view, there is a concensus that the SM can only be a low energy limit of a more complete theory. It is thus of the utmost importance to try and push to the limit in finding possible deviations from the SM. In fact, there are systematic programs for such precision tests. Possible deviations from the SM can all be summarized into a few parameters which then serve to measure the effects of new physics beyond the SM. A lot of efforts have gone into this type of investigation trying to develop a scheme to minimize the disadvantage of having unkown m_t but to optimize sensitivity to new physics. To date significant constraints have been placed on a number of models, such as the two Higgs doublet model(2HDM)[3], the minimal supersymmetric model(MSSM)[4], the technicolor model[5], and some extended gauge models[6]. In this work we wish to apply the analysis to another extension of the SM, the $Sp(6)_L \times U(1)_Y$ family model. Amongst several of the available parametrization schemes in the literature, the most appropriate one for our purposes is that of Altarelli et. al[7]. This is because their ϵ-parametrization can be used for new physics which might appear at energy scales not far from those of the SM. This is the case for the $Sp(6)_L \times U(1)_Y$ model. In fact, in an earlier analysis[21] we have performed precision EW tests in this model in a scheme using $\epsilon_{1,2,3}$ introduced in Ref. [7]. We found that the parameters in this model were severely constrained. Recently, it was re-emphasized that there are important vertex corrections to the decay mode $Z \to b\bar{b}$[3, 17, 18]. This mode has also been measured at LEP and has proven to provide a strong constraint to model building. Considering the high central value for the m_t from CDF, $Z \to b\bar{b}$ vertex corrections, which grow as m_t^2, can be quite significant. Therefore, we have now incorporated $Z \to b\bar{b}$ vertex corrections in our new analysis of the $Sp(6)_L \times U(1)_Y$ model. In this paper we extend our previous analysis in two aspects: (i) we include a new parameter ϵ_b to encode $Z \to b\bar{b}$ vertex corrections, (ii) we calculate ϵ_1 in a new scheme introduced in Ref [17] in order to take advantage of all LEP data. We find that inclusion of $Z \to b\bar{b}$ vertex corrections reinforces strongly the previous constraint from ϵ_1 only so that the allowed parameter regions are reduced considerably. Thus, the precision EW tests have demonstrated clearly that they are powerful tools in shaping our searches for extensions of the SM.

In Sec. II, we will describe the $Sp(6)_L \times U(1)_Y$ model, spelling out in detail the parts that are relevant to precision tests. In Sec. III, we summarize properties of the ϵ-parameters which will be used in our analysis. Sec. IV contains our detailed numerical results. Finally, some concluding remarks are given in Sec. V.

2 $Sp(6)_L \times U(1)_Y$ Model

The $SP(6)_L \otimes U(1)_Y$ model, proposed some time ago[8], is the simplest extension of the standard model of three generations that unifies the standard $SU(2)_L$ with the horizontal gauge group $G_H(= SU(3)_H)$ into an anomaly free, simple, Lie group. In this model, the six left-handed quarks (or leptons) belong to a **6** of $SP(6)_L$, while the right-handed fermions are all singlets. It is thus a straightforward generalization of $SU(2)_L$ into $SP(6)_L$, with

the three doublets of $SU(2)_L$ coalescing into a sextet of $SP(6)_L$. Most of the new gauge bosons are arranged to be heavy ($\geq 10^2$–10^3 TeV) so as to avoid sizable FCNC. $SP(6)_L$ can be naturally broken into $SU(2)_L$ through a chain of symmetry breakings. The breakdown $SP(6)_L \to [SU(2)]^3 \to SU(2)_L$ can be induced by two antisymmetric Higgs which tranform as $(\mathbf{1}, \mathbf{14}, 0)$ under $SU(3)_C \otimes SP(6)_L \otimes U(1)_Y$. The standard $SU(2)_L$ is to be identified with the diagonal $SU(2)$ subgroup of $[SU(2)]^3 = SU(2)_1 \otimes SU(2)_2 \otimes SU(2)_3$, where $SU(2)_i$ operates on the ith generation exclusively. In terms of the $SU(2)_i$ gauge boson $\vec{A}_i$, the $SU(2)_L$ gauge bosons are given by $\vec{A} = \frac{1}{\sqrt{3}}(\vec{A}_1 + \vec{A}_2 + \vec{A}_3)$. Of the other orthogonal combinations of $\vec{A}_i$, $\vec{A}' = \frac{1}{\sqrt{6}}(\vec{A}_1 + \vec{A}_2 - 2\vec{A}_3)$, which exhibits unversality only among the first two generations, can have a mass scale in the TeV range [9]. The three gauge bosons A' will be denoted as Z' and $W'^{\pm}$. Given these extra gauge bosons with mass in the TeV range, we can expect small deviations from the SM. Some of these effects were already analyzed elsewhere. For EW precision tests, the dominant effects of new heavier gauge boson $Z'(W'^{\pm})$ show up in its mixing with the standard $Z(W^{\pm})$ to form the mass eigenstates $Z_{1,2}(W_{1,2})$:

$$Z_1 = Z\cos\phi_Z + Z'\sin\phi_Z\ , \qquad Z_2 = -Z\sin\phi_Z + Z'\cos\phi_Z\ , \tag{1}$$

$$W_1 = W\cos\phi_W + W'\sin\phi_W\ , \qquad W_2 = -W\sin\phi_W + W'\cos\phi_W\ , \tag{2}$$

where $Z_1(W_1)$ is identified with the physical $Z(W)$. Here, the mixing angles ϕ_Z and ϕ_W are expected to be small ($\lesssim 0.01$), assuming that they scale as some powers of mass ratios.

With the additional gauge boson Z', the neutral-current Lagrangian is generalized to contain an additional term

$$L_{NC} = g_Z J_Z^\mu Z_\mu + g_{Z'} J_{Z'}^\mu Z'_\mu\ , \tag{3}$$

where $g_{Z'} = \sqrt{\frac{1-x_W}{2}}\, g_Z = \frac{g}{\sqrt{2}}$, $x_W = \sin^2\theta_W$, and $g = \frac{e}{\sin\theta_W}$. The neutral currents J_Z and $J_{Z'}$

are given by

$$J_Z^\mu = \sum_f \bar\psi_f \gamma^\mu \left(g_V^f + g_A^f \gamma_5\right) \psi_f \,, \tag{4}$$

$$J_{Z'}^\mu = \sum_f \bar\psi_f \gamma^\mu \left(g_V^{\prime f} + g_A^{\prime f} \gamma_5\right) \psi_f \,, \tag{5}$$

where $g_V^f = \frac{1}{2}(I_{3L} - 2x_W q)_f$, $g_A^f = \frac{1}{2}(I_{3L})_f$ as in SM, $g_V^{\prime f} = g_A^{\prime f} = \frac{1}{2}(I_{3L})_f$ for the first two generations and $g_V^{\prime f} = g_A^{\prime f} = -(I_{3L})_f$ for the third. Here $(I_{3L})_f$ and q_f are the third component of weak isospin and electric charge of fermion f, respectively. And the neutral-current Lagrangian reads in terms of $Z_{1,2}$

$$L_{NC} = g_Z \sum_{i=1}^{2} \sum_f \bar\psi_f \gamma_\mu \left(g_{Vi}^f + g_{Ai}^f \gamma_5\right) \psi_f Z_i^\mu \,, \tag{6}$$

where g_{Vi}^f and g_{Ai}^f are the vector and axial-vector couplings of fermion f to physical gauge boson Z_i, respectively. They are given by

$$g_{V1,A1}^f = g_{V,A}^f \cos\phi_Z + \frac{g_{Z'}}{g_Z} g_{V,A}^{\prime f} \sin\phi_Z \,, \tag{7}$$

$$g_{V2,A2}^f = -g_{V,A}^f \sin\phi_Z + \frac{g_{Z'}}{g_Z} g_{V,A}^{\prime f} \cos\phi_Z \,. \tag{8}$$

Similar analysis can be carried out in the charged sector.

3 One-loop EW radiative corrections and the ϵ- parameters

There are several different schemes to parametrize the EW vacuum polarization corrections [12, 13, 14, 15]. It can be easily shown that by expanding the vacuum polarization tensors

to order q^2, one obtains three independent physical parameters. Alternatively, one can show that upon symmetry breaking there are three additional terms in the effective lagrangian [14]. In the (S, T, U) scheme [13], the deviations of the model predictions from those of the SM (with fixed values of m_t, m_H) are considered to be as the effects from "new physics". This scheme is only valid to the lowest order in q^2, and is therefore not viable for a theory with new, light ($\sim M_Z$) particles. In the ϵ-scheme, on the other hand, the model predictions are absolute and are valid up to higher orders in q^2, and therefore this scheme is better suited to the EW precision tests of the MSSM[16] and a class of supergravity models [19]. Here we choose to use the ϵ-scheme because the new particles in the model to be considered here can be relatively light ($O(1TeV)$).

There are two different ϵ-schemes. The original scheme[7] was considered in our previous analysis [21], where $\epsilon_{1,2,3}$ are defined from a basic set of observables Γ_l, A_{FB}^l and M_W/M_Z. Due to the large m_t-dependent vertex corrections to Γ_b, the $\epsilon_{1,2,3}$ parameters and Γ_b can be correlated only for a fixed value of m_t. Therefore, Γ_{tot}, Γ_{hadron} and Γ_b were not included in Ref. [7]. However, in the new ϵ-scheme, introduced recently in Ref. [17], the above difficulties are overcome by introducing a new parameter ϵ_b to encode the $Z \to b\bar b$ vertex corrections. The four ϵ's are now defined from an enlarged set of Γ_l, Γ_b, A_{FB}^l and M_W/M_Z without even specifying m_t. In this work we use this new ϵ-scheme. Experimental values for ϵ_1 and ϵ_b are determined by including all the latest LEP data(complete '92 LEP data+ preliminary '93 LEP data) to be [27]

$$\epsilon_1^{exp} = (-0.3 \pm 3.2) \times 10^{-3}, \qquad \epsilon_b^{exp} = (3.1 \pm 5.5) \times 10^{-3} \,. \tag{9}$$

The expression for ϵ_1 is given as [16]

$$\epsilon_1 = e_1 - e_5 - \frac{\delta G_{V,B}}{G} - 4\delta g_A, \tag{10}$$

where $e_{1,5}$ are the following combinations of vacuum polarization amplitudes

$$e_1 = \frac{\alpha}{4\pi \sin^2\theta_W M_W^2}[\Pi_T^{33}(0) - \Pi_T^{11}(0)], \tag{11}$$

$$e_5 = M_Z^2 F'_{ZZ}(M_Z^2), \tag{12}$$

and the $q^2 \neq 0$ contributions $F_{ij}(q^2)$ are defined by

$$\Pi_T^{ij}(q^2) = \Pi_T^{ij}(0) + q^2 F_{ij}(q^2). \tag{13}$$

The quantities $\delta g_{V,A}$ are the contributions to the vector and axial-vector form factors at $q^2 = M_Z^2$ in the $Z \to l^+l^-$ vertex from proper vertex diagrams and fermion self-energies, and $\delta G_{V,B}$ comes from the one-loop box, vertex and fermion self-energy corrections to the μ-decay amplitude at zero external momentum. It is important to note that these non-oblique corrections are non-negligible. Also, they must be included since in general only the physical observables ϵ_i, but not the individual terms in them, are gauge-invariant[20]. However, we have included the Standard non-oblique corrections only. The contributions from the new physics are small, at least in the gauge that we choose, and will be neglected here.

Following Ref. [17], $Z \to b\bar{b}$ vertex corrections are encoded in a new variable ϵ_b defined from Γ_b, the inclusive partial width for $Z \to b\bar{b}$, as follows

$$\Gamma_b = 3R_{QCD}\frac{G_F M_Z^3}{6\pi\sqrt{2}}\left(1+\frac{\alpha}{12\pi}\right)\left[\beta_b\frac{(3-\beta_b^2)}{2}(g_V^b)^2 + \beta_b^3(g_A^b)^2\right], \tag{14}$$

with

$$R_{QCD} \cong \left[1+\frac{\alpha_S(M_Z)}{\pi} - 1.1\left(\frac{\alpha_S(M_Z)}{\pi}\right)^2 - 12.8\left(\frac{\alpha_S(M_Z)}{\pi}\right)^3\right], \tag{15}$$

$$\beta_b = \sqrt{1-\frac{4m_b^2}{M_Z^2}}, \tag{16}$$

$$g_A^b = -\frac{1}{2}\left(1+\frac{\epsilon_1}{2}\right)(1+\epsilon_b), \tag{17}$$

$$\frac{g_V^b}{g_A^b} = \frac{1-\frac{4}{3}\bar{s}_W^2+\epsilon_b}{1+\epsilon_b}. \tag{18}$$

Here $\bar{s}_W^2$ is an effective $\sin^2\theta_W$ for on-shell Z, and ϵ_b is closely related to the real part of the vertex correction to $Z \to b\bar{b}$, denoted by $\delta_{b-Vertex}$ and defined explicitly in Ref. [22]. In the SM, the diagrams for $\delta_{b-Vertex}$ involve top quarks and $W^{\pm}$ bosons, and the contribution to ϵ_b depends quadratically on m_t, which is due to the EW symmetry breaking and can be a decisive test of the model. In supersymmetric models there are additional diagrams involving Higgs bosons and supersymmetric particles[24, 23]. In fact, ϵ_b has been calculated by one of us(G.P) in the context of non-supersymmetric two Higgs doublet model[25].

In the following section we calculate ϵ_1 and ϵ_b in the $Sp(6)_L \times U(1)_Y$ model. We do not, however, include $\epsilon_{2,3}$ in our analysis simply because these parameters can not provide any constraints at the current level of experimental accuracy[19]. Although the oblique corrections due to extra gauge bosons could be neglected completely as in Ref[6], we have improved the model predictions for the oblique corrections by implementing the new vertices from Eq. (6) for the fermion loops only. In this way we have accounted for a significant deviation of the model prediction from the SM value for not so small $|\phi_{Z,W}|$. Furthermore, in models with extra gauge bosons such as the model to be considered here, the contribution from the mixings of these extra bosons with the SM ones ($\Delta\rho_M$) should also be added to ϵ_1[6, 28, 31].

4 Results and Discussion

In order to calculate the model prediction for the Z width, it is sufficient for our purposes to resort to the improved Born approximation (IBA)[29], neglecting small additional effects from the new physics. Weak corrections can be effectively included within the IBA, wherein the vector couplings of all the fermions are determined by an effective weak mixing angle. In the case $f \neq b$, vertex corrections are negligible, and one obtains the standard partial Z width

$$\Gamma(Z \longrightarrow f\bar{f}) = N_C^f \rho \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left(1 + \frac{3\alpha}{4\pi} q_f^2\right) \left[\beta_f \frac{(3-\beta_f^2)}{2} {g_{V1}^f}^2 + \beta_f^3 {g_{A1}^f}^2\right] , \tag{19}$$

where $N_C^f = 1$ for leptons, and for quarks

$$N_C^f \cong 3\left[1 + \frac{\alpha_S(M_Z)}{\pi} - 1.1\left(\frac{\alpha_S(M_Z)}{\pi}\right)^2 - 12.8\left(\frac{\alpha_S(M_Z)}{\pi}\right)^3\right] , \tag{20}$$

$$\beta_f = \sqrt{1 - \frac{4m_f^2}{M_Z^2}} , \tag{21}$$

$$\rho = 1 + \Delta\rho_M + \Delta\rho_{SB} + \Delta\rho_t , \tag{22}$$

$$\Delta\rho_t \simeq \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} . \tag{23}$$

where the ρ parameter includes not only the effects of the symmetry breaking $(\Delta\rho_{SB})$[30] and those of the mixings between the SM bosons and the new bosons $(\Delta\rho_M)$, but also the loop effects $(\Delta\rho_t)$. N_C^f above is obtained by accounting for QCD corrections up to 3-loop order in $\overline{MS}$ scheme, and we ignore different QCD corrections for vector and axial-vector couplings which are due not only to chiral invariance broken by masses but also the large mass splitting between b and t. We use for the vector and axial vector couplings g_{V1}^f and g_{A1}^f

in Eq. (7) the effective $\sin^2\theta_W$, $\bar{x}_W = 1 - \frac{M_W^2}{\rho M_Z^2}$. In the case of $Z \longrightarrow b\bar{b}$, the large t vertex correction should be accounted for by the following replacement

$$\rho \longrightarrow \rho - \frac{4}{3}\Delta\rho_t , \quad \bar{x}_W \longrightarrow \bar{x}_W \left(1 + \frac{2}{3}\Delta\rho_t\right) . \tag{24}$$

In the following analysis, we consider not only a constraint on the deviation of Γ_Z from the SM prediction[31], $\Delta\Gamma_Z \leq 14$ MeV, which is the present experimental accuracy[33], but also the present experimental bound on $\Delta\rho_M$. We use a direct model-independent bound on $\Delta\rho_M$, $\Delta\rho_M \lesssim 0.0147 - 0.0043\left(\frac{m_t}{120GeV}\right)^2$ from $1 - (\frac{M_W}{M_Z})^2 = 0.2257 \pm 0.0017$ and $M_Z = 91.187 \pm 0.007$ GeV[33]. The values $M_H = 100$ GeV, $\alpha_S(M_Z) = 0.118$, and $\alpha(M_Z) = 1/128.87$ will be used thoughout the numerical analysis.

In Fig. 1 we present the model predictions for ϵ_1 and ϵ_b only for the values of ϕ_Z and ϕ_W allowed by $\Delta\Gamma_Z$ and $\Delta\rho_M$ constraints with $M_{Z'} = 1000$ and $M_{W'} = 800$ GeV for $m_t = 160, 175$ and 190 GeV. We restrict $|\phi_{Z,W}| \leq 0.02$. We also include in the figure the latest 90%CL ellipse from all LEP data[27]. The values of m_t used are as indicated over each horizontal stripe of dotts. It is very interesting for one to see that the correlated contraint is much stronger than individual constraints. The maximum deviation of ϵ_b in the model from the SM value is around 1.3% for $|\phi_{Z,W}| \lesssim 0.02$. Although the deviation is very small, the inclusion of the ϵ_b in the analysis makes the LEP data certainly much more constraining. Imposing the $\epsilon_1 - \epsilon_b$ constraint by selecting only the values of ϕ_Z and ϕ_W falling inside the ellipse in Fig. 1, we show in Fig. 2 the allowed regions in (ϕ_Z, ϕ_W) for (a) $m_t = 160$ GeV, (b) $m_t = 175$ GeV and (c) $m_t = 190$ GeV. The striking difference in the shape of the allowed region between $m_t = 175$ GeV and $m_t = 190$ GeV comes from the fact that the SM value of ϵ_1 for $m_t = 175$ GeV is inside the ellipse whereas the one for $m_t = 190$ GeV is outside[21].

If the top quark turns out to be fairly heavy, e.g. $m_t \gtrsim 180$ GeV where the SM predictions always fall outside the ellipse in the Fig. 1 , then the presence of the extra gauge bosons is certainly favored because it can bring the model predictions inside the ellipse as seen in Fig. 1 although there is an ambiguity in the model prediction for ϵ_1 that the contribution from the extra gauge bosons can have either signs. This situation can be contrasted with the one in the MSSM where the heavy top quark is still consistent with the LEP data as long as the chargino is very light $\sim M_Z/2$, which is known as "light chargino effect"[16], whose contribution to ϵ_1 is always negative. However, if the chargino were not discovered at LEP II, then MSSM would fall into a serious trouble.

5 Conclusions

In this work we have extended our previous work on the precision EW tests in the $Sp(6)_L \times U(1)_Y$ family model to include for the first time the important $Z \rightarrow b\bar{b}$ vertex corrections encoded in a new variable ϵ_b, utilizing all the latest LEP data. As has been the case with similar studies, the model is considerably constrained. The most important effects of the model come from mixings of the SM gauge bosons Z and W with the additional gauge bosons Z' and W'. We have included in our analysis the one loop EW radiative corrections due to the new bosons in terms of $\epsilon_{1,b}$ and $\Delta\Gamma_Z$. It is found that the correlation between ϵ_1 and ϵ_b makes the combined $\epsilon_1 - \epsilon_b$ constraint much stronger than the individual ones. Using a global fit to LEP data on $\Gamma_l, \Gamma_b, A^l_{FB}$ and M_W/M_Z measurement, we find that the mixing angles ϕ_Z and ϕ_W are constrained to lie in rather small regions. Also, larger ($\gtrsim 1\%$) ϕ_Z and ϕ_W values are allowed only when there is considerable cancellation between the Z' and W' contributions, corresponding to $|\phi_Z| \approx |\phi_W|$. It is noteworthy that the results are sensitive to the top quark mass. For smaller m_t's, the allowed parameter regions become considerably larger. Only very tiny regions are allowed for $m_t = 190\,\mathrm{GeV}$. It is very interesting for one to see that the model can not accomodate $m_t \gtrsim 195\,\mathrm{GeV}$ at 90%CL, which is still consistent

with the m_t from CDF. As the top quark mass from the Tevatron becomes more accurate, we can narrow down the mixing angles further with considerable precision.

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Figure Captions

- Figure 1: The correlated predictions for the ϵ_1 and ϵ_b parameters in the unit of 10^{-3} in the $Sp(6)_L \times U(1)_Y$ model. The ellipse represents the 90%CL contour obtained from all LEP data including the preliminary 1993 data. The values of m_t are as indicated. $M_{Z'} = 1000\,\text{GeV}$ and $M_{W'} = 800\,\text{GeV}$ are used. The dotts represent the values of ϕ_Z and ϕ_W allowed by $\Delta\Gamma_Z \leq 14\,\text{MeV}$ and $\Delta\rho_M$ constraint with $|\phi_{Z,W}| \leq 0.02$.

- Figure 2: The model parameter space allowed by the further contraint from ϵ_1-ϵ_b using the 90%CL contour in Figure 1 for (a) $m_t = 160\,\text{GeV}$, (b) $m_t = 175\,\text{GeV}$ and (c) $m_t = 190\,\text{GeV}$. $M_{Z'} = 1000\,\text{GeV}$ and $M_{W'} = 800\,\text{GeV}$ are used.

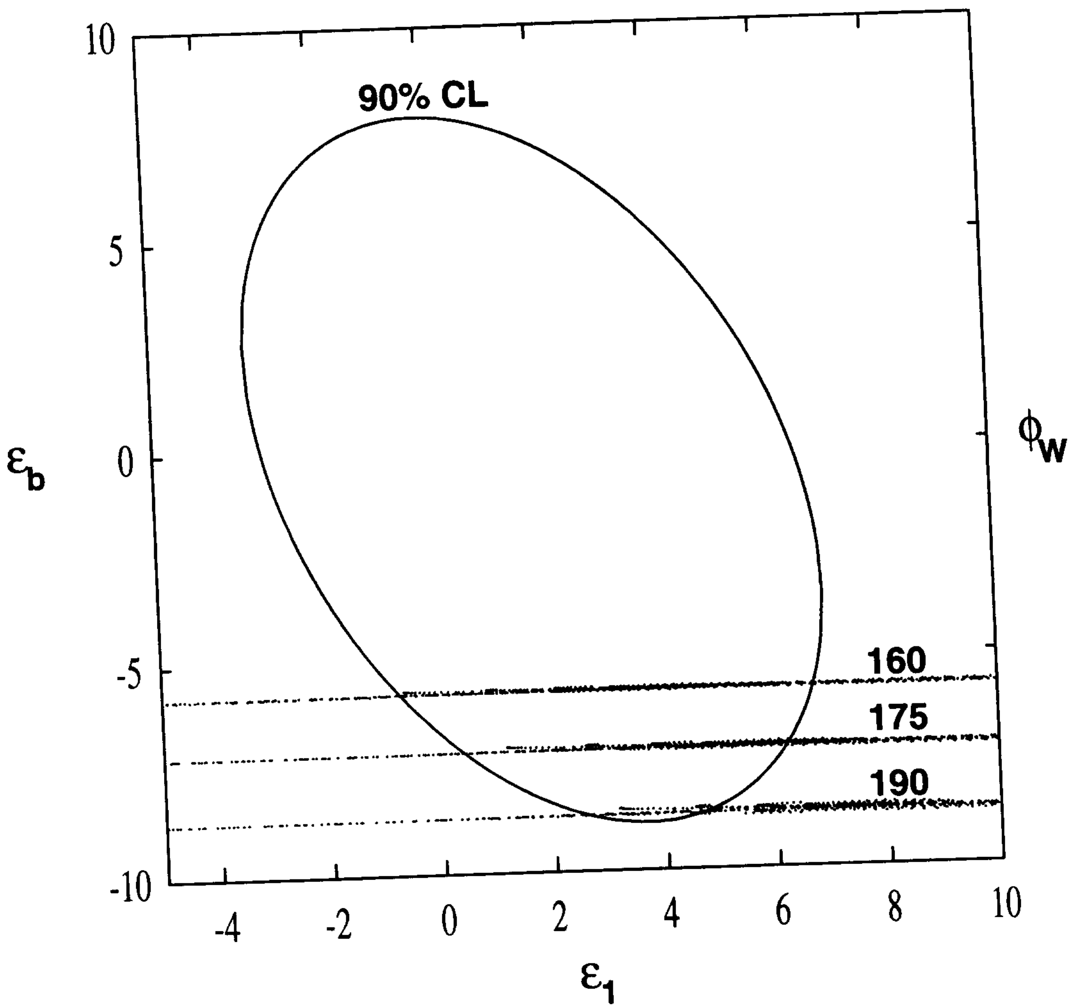

Figure 1

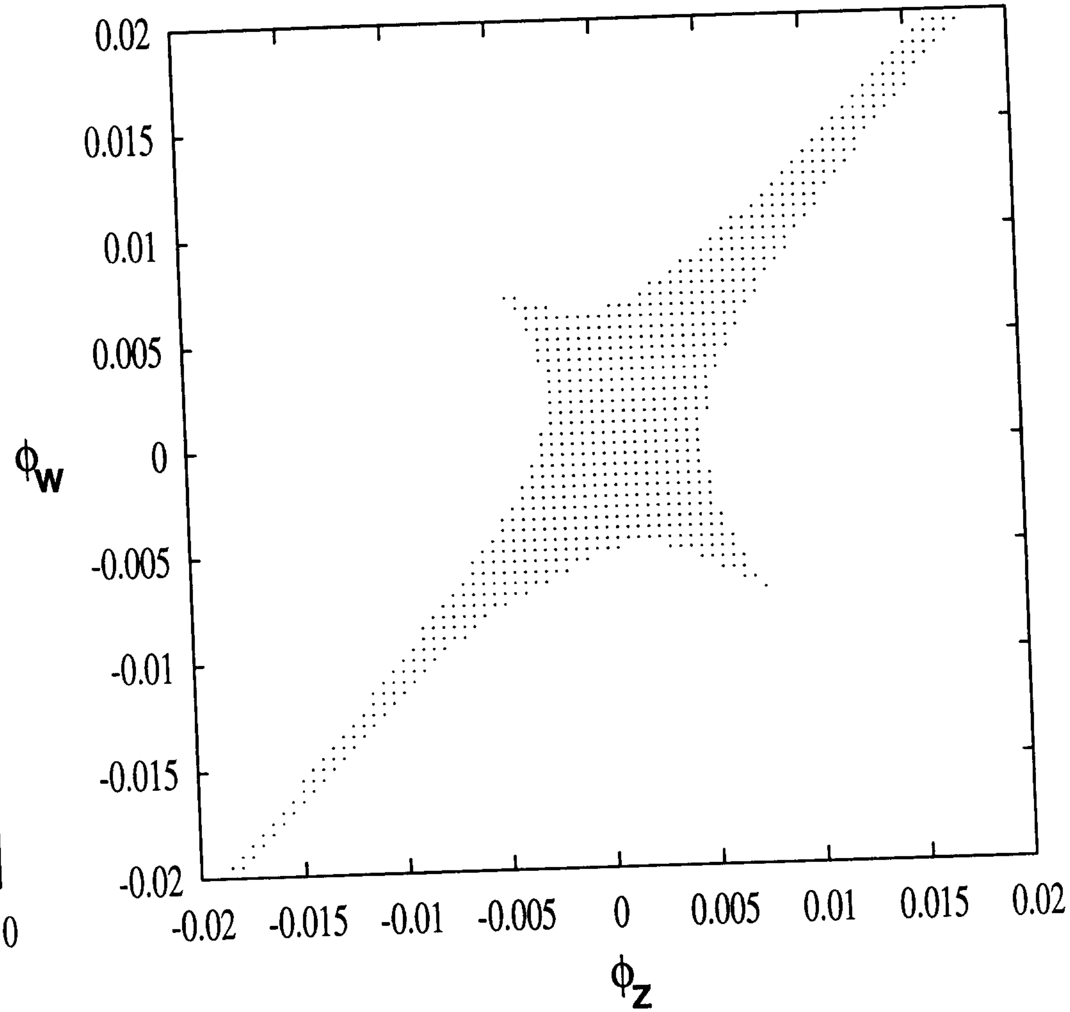

Figure 2a

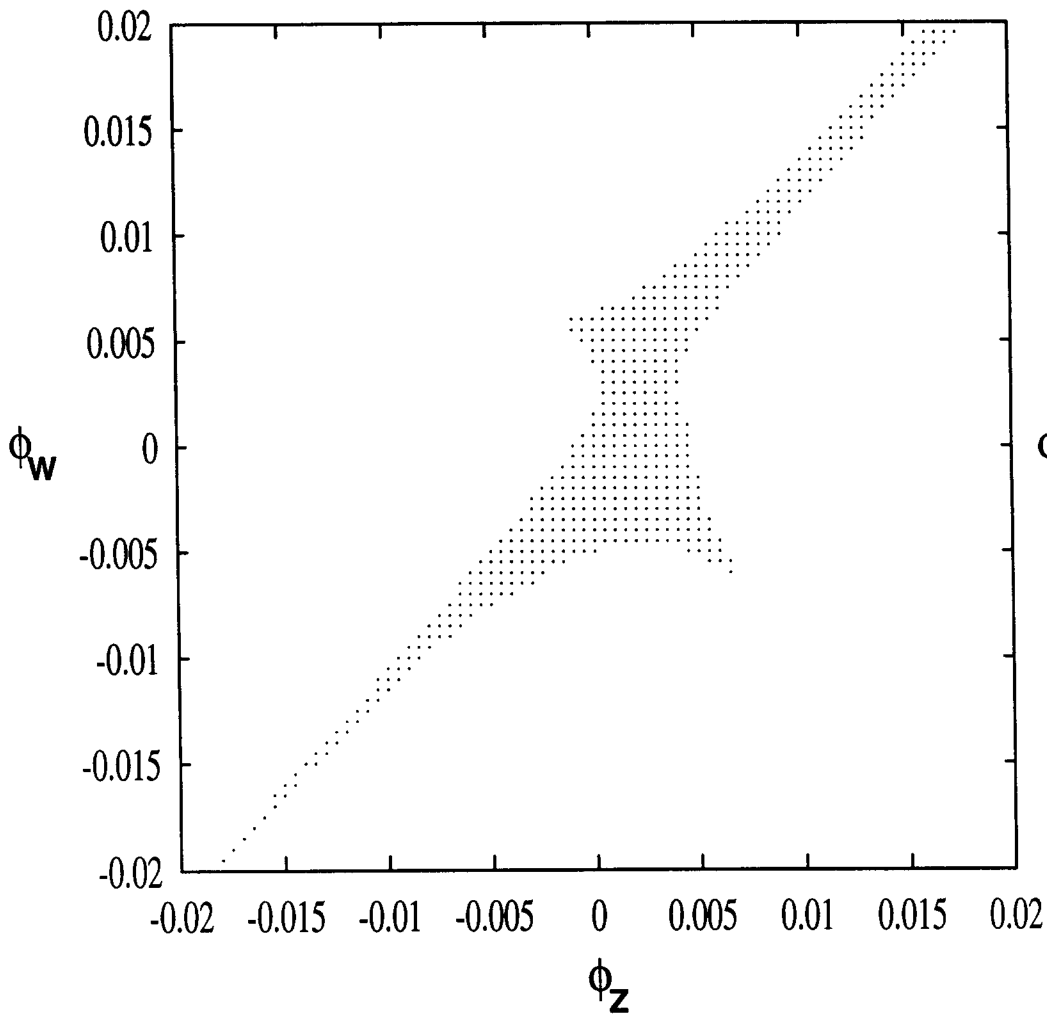

Figure 2b

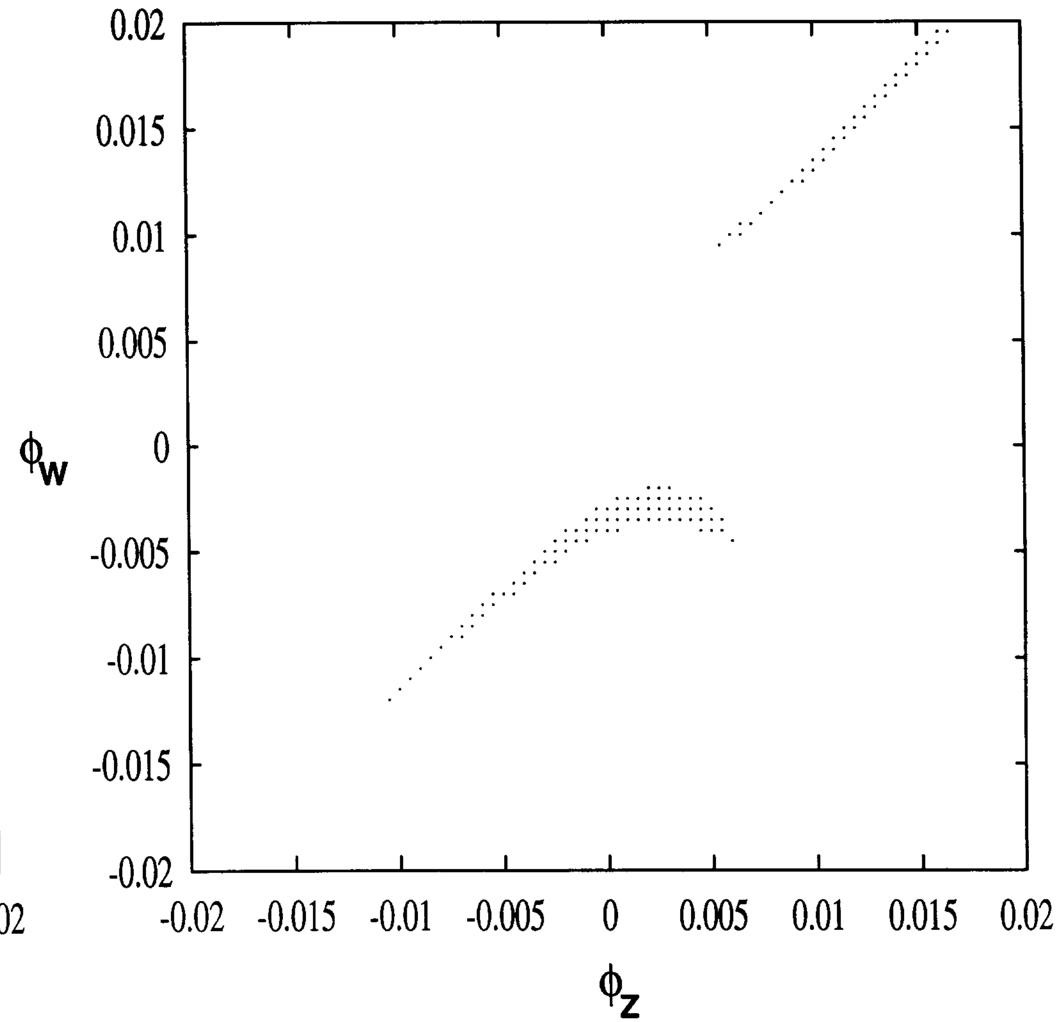

Figure 2c