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Precision Electroweak Tests on the $Sp(6)_L \times U(1)_Y$ Model

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ABSTRACT

We perform precision electroweak tests on the $Sp(6)_L \times U(1)_Y$ model. The purpose of the analysis is to delineate the model parameters such as the mixing angles of the extra gauge bosons present in this model. We find that the model is already constrained considerably by the present LEP data.

1 Introduction

Precision measurements at the LEP have been extremely successful in confirming the validity of the Standard Model(SM)[1]. 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 top quark mass(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)[2], the minimal supersymmetric model(MSSM)[3], the technicolor model[4], and some extended gauge models[5]. 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[6]. 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. We still find that parameters in this model are severely constrained. 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[7], 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 [8]. 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 $Z_{1,2}(W_{1,2})$:

$$\begin{aligned} Z_1 &= Z\cos\phi_Z + Z'\sin\phi_Z \;, & Z_2 &= -Z\sin\phi_Z + Z'\cos\phi_Z \;, & (1)\\ W_1 &= W\cos\phi_W + W'\sin\phi_W \;, & W_2 &= -W\sin\phi_W + W'\cos\phi_W \;, & (2)\end{aligned}$$

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

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

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

where $g_V^f = \frac{1}{2}\left(I_{3L} - 2x_W q\right)_f$, $g_A^f = \frac{1}{2}\left(I_{3L}\right)_f$ as in SM, $g_V'^f = g_A'^f = \frac{1}{2}\left(I_{3L}\right)_f$ for the first two generations and $g_V'^f = g_A'^f = -\left(I_{3L}\right)_f$ for the third. Here $\left(I_{3L}\right)_f$ 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

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

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

Similar analysis can be carried out in the charged sector.

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

It is now well known that EW parameters become consistent with the data only if the EW radiative corrections are accounted for. For example, the predictions for $\sin^2\theta_w$ and M_W, obtained from various measurements at M_Z and low-energy ν scattering experiments are consistent only if one-loop effects are included.

There are several different schemes to parametrize the EW vacuum polarization corrections [11, 12, 13, 14]. 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 [13]. In the (S, T, U) scheme [12], 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 ($O(1TeV)$). In this scheme,three independent physical parameters $\epsilon_{1,2,3}$ [14] correspond to a set of observables Γ_l, A^l_{FB} and M_W/M_Z. Among these three parameters, only ϵ_1 provides very strong constraint , for example, in supersymmetric models[18, 19]. The expressions for $\epsilon_{1,2,3}$ are given as [16, 19]

$$\begin{aligned}
\epsilon_1 &= e_1 - e_5 - \frac{\delta G_{V,B}}{G} - 4\delta g_A\,, && (9)\\
\epsilon_2 &= e_2 - s^2 e_4 - c^2 e_5 - \frac{\delta G_{V,B}}{G} - \delta g_V - 3\delta g_A\,, && (10)\\
\epsilon_3 &= e_3 + c^2 e_4 - c^2 e_5 + \frac{c^2 - s^2}{2s^2}\delta g_V - \frac{1+2s^2}{2s^2}\delta g_A\,, && (11)
\end{aligned}$$

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

$$\begin{aligned}
e_1 &= \frac{\alpha}{4\pi \sin^2\theta_W M_W^2}[\Pi_T^{33}(0) - \Pi_T^{11}(0)]\,, && (12)\\
e_2 &= F_{WW}(M_W^2) - \frac{\alpha}{4\pi s^2} F_{33}(M_Z^2)\,, && (13)\\
e_3 &= \frac{\alpha}{4\pi s^2}[F_{3Q}(M_Z^2) - F_{33}(M_Z^2)]\,, && (14)\\
e_4 &= F_{\gamma\gamma}(0) - F_{\gamma\gamma}(M_Z^2)\,, && (15)\\
e_5 &= M_Z^2 F'_{ZZ}(M_Z^2)\,, && (16)
\end{aligned}$$

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

$$\Pi_T^{ij}(q^2) = \Pi_T^{ij}(0) + q^2 F_{ij}(q^2). \qquad (17)$$

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 $Z \rightarrow l^+l^-$ 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 SM corrections are non-negligible, and must be included in order to obtain an accurate SM prediction. In the following section we calculate ϵ_1 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[15, 19]. We assume throughout the analysis that the non-oblique contributions from new physics to the measurables that are included in the global fit are negligible. Although loop corrections due to extra gauge bosons could be neglected completely as in Ref[5], we have improved the model prediction 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[5, 20, 23].

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)[21], 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

$$\Gamma(Z \longrightarrow f\bar{f}) = N_C^f \rho \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left(1 + \frac{3\alpha}{4\pi} q_f^2\right) \left[\beta_f \frac{\left(3 - \beta_f^2\right)}{2} {g_{V1}^f}^2 + \beta_f^3 {g_{A1}^f}^2\right] , \tag{18}$$

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

$$N_C^f \cong 3\left[1 + 1.2\frac{\alpha_S(M_Z)}{\pi} - 1.1\left(\frac{\alpha_S(M_Z)}{\pi}\right)^2 - 12.8\left(\frac{\alpha_S(M_Z)}{\pi}\right)^3\right] , \tag{19}$$

$$\beta_f = \sqrt{1 - \frac{4m_f^2}{M_Z^2}} , \tag{20}$$

$$\rho = 1 + \Delta\rho_M + \Delta\rho_{SB} + \Delta\rho_t , \tag{21}$$

$$\Delta\rho_t \simeq \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} . \tag{22}$$

where the ρ parameter includes not only the effects of the symmetry breaking $(\Delta\rho_{SB})$[22] 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

$$\rho \longrightarrow \rho - \frac{4}{3}\Delta\rho_t\,, \quad \bar{x}_W \longrightarrow \bar{x}_W\left(1 + \frac{2}{3}\Delta\rho_t\right)\,. \tag{23}$$

In the following analysis, we use the recent experimental value, $\epsilon_1 = (-0.9 \pm 3.7) \times 10^{-3}$, obtained from a global fit to LEP data on $\Gamma_l, A_{FB}^{l,b}, A_{pol}^{\tau}$ and M_W/M_Z measurement[15, 19]. We consider not only a constraint on the deviation of Γ_Z from the SM prediction[23], $\Delta\Gamma_Z \leq 14$ MeV, which is the present experimental accuracy[25], 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 $M_Z = 91.187 \pm 0.007\,\text{GeV}$[25]. The values $M_H = 100\,\text{GeV}$, $\alpha_S(M_Z) = 0.118$, and $\alpha(M_Z) = 1/128.87$ will be used thoughout the numerical analysis.

In Fig. 1 we present the regions in the (ϕ_W, ϕ_Z) plane excluded by all the constraints to be imposed here for $m_t = 130$, $M_{Z'} = 1000$, and $M_{W'} = 800\,\text{GeV}$. An excluded region shaded by horizontal lines represents the ϵ_1 constraint at 90%C. L. whereas the one by vertical lines corresponds to $\Delta\Gamma_Z$ and $\Delta\rho_M$ constraints. We observe in Fig. 1 that ϵ_1 starts cutting in the region ($\phi_Z \lesssim -0.007$ and $\phi_W \gtrsim 0.009$) still allowed by the other constraints even at $m_t = 130\,\text{GeV}$. Similarly in Fig. 2 we also show the excluded regions for $m_t = 170$, $M_{Z'} = 800$, and $M_{W'} = 1000\,\text{GeV}$. It's very interesting for one to see two small disconnected allowed regions in the figure. We find here that $\phi_Z \gtrsim 0$ and $\phi_W \gtrsim 0.005$ in one region whereas $\phi_Z \gtrsim -0.0075$ and $\phi_W \gtrsim -0.002$ in the other. The way that values for $M_{Z'}$ and $M_{W'}$ are chosen originates from constraint due to $\Delta\rho_M$. For $m_t = 170\,\text{GeV}$, the model predicts ϵ_1 without $\Delta\rho_M$ too high to be allowed at 90%C. L. for $|\phi_{Z,W}| \lesssim 0.01$. Therefore, the model parameters including $M_{Z'}$ and $M_{W'}$ are chosen in such a way that $\Delta\rho_M$ brings ϵ_1 down to or below the LEP bound at 90%C. L. This is fulfilled only if $M_{Z'} < M_{W'}$. However, for $m_t = 130\,\text{GeV}$, $M_{Z'} < M_{W'}$ or $M_{Z'} > M_{W'}$ are allowed because now ϵ_1 lies always within the LEP bounds for $|\phi_{Z,W}| \lesssim 0.01$. For $M_{Z'} > M_{W'}$, $\Delta\rho_M$ brings ϵ_1 up to the LEP upper limit(0.0052) at 90%C. L. while for $M_{Z'} < M_{W'}$ it brings ϵ_1 down to the LEP lower limit(-0.007). Since the contour lines for the one choice are more or less those for the other choice with 90 deg rotation around zero, we present in Fig. 1 only one choice, $M_{Z'} > M_{W'}$. Moreover, for $m_t = 170\,\text{GeV}$, there are in fact two pairs of contour lines for ϵ_1 constraint. The pairs come from either the LEP upper limit or the lower limit because ϵ_1 can also go below the lower limit because of a large negative constribution from $\Delta\rho_M$ for large mixing angles.

5 Conclusions

In this work we have concentrated on the constraints placed on the $Sp(6)_L \times U(1)_Y$ family model from precision LEP measurements. As has been the cae with similar studies, the model is severely 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 computed the one loop EW radiative corrections due to the new bosons in terms of ϵ_1 and $\Delta\Gamma_Z$. Using a global fit to LEP data on $\Gamma_l, A_{FB}^{l,b}, A_{pol}^{\tau}$ 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 small m_t (130 GeV), the allowed parameter regions are considerably bigger than those for larger m_t (170 GeV) values. Hopefully, when the top quark mass becomes available, we can narrow down the mixing angles with considerable precision.

Acknowledgements

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Figure Captions

Figure 1: The region excluded by the ϵ_1 constraint at 90% C. L.(horizontal). The region excluded by $\Delta\Gamma_Z \leq 14MeV$ and $\Delta\rho_M$ constraint (vertical). $m_t = 130$ GeV, $M_{Z'} = 1000$ GeV, and $M_{W'} = 800$ GeV are used.

Figure 2: Same as in Figure. 1 except that $m_t = 170$ GeV, $M_{Z'} = 800$ GeV, and $M_{W'} = 1000$ GeV are used.

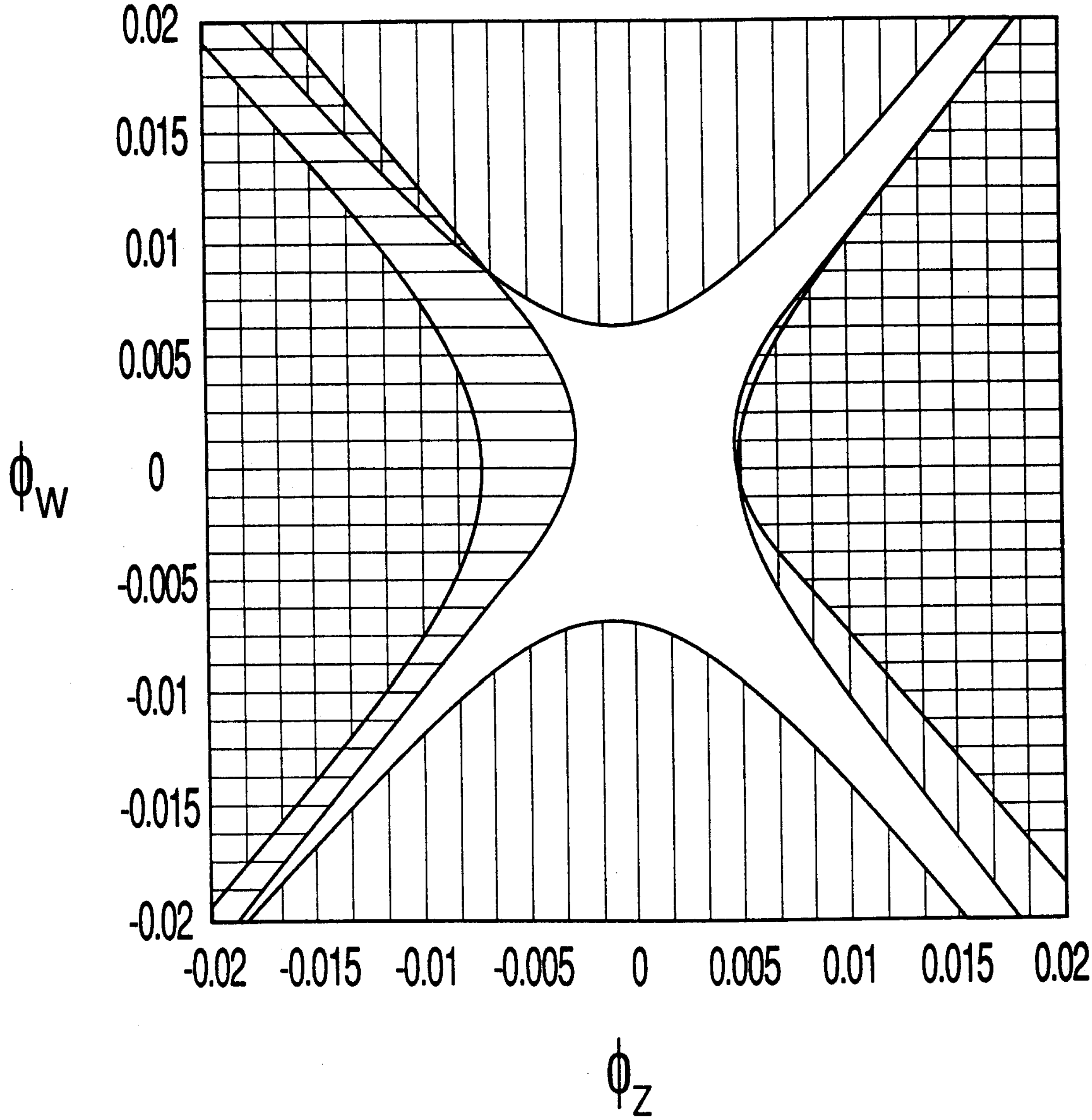
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Figure 1

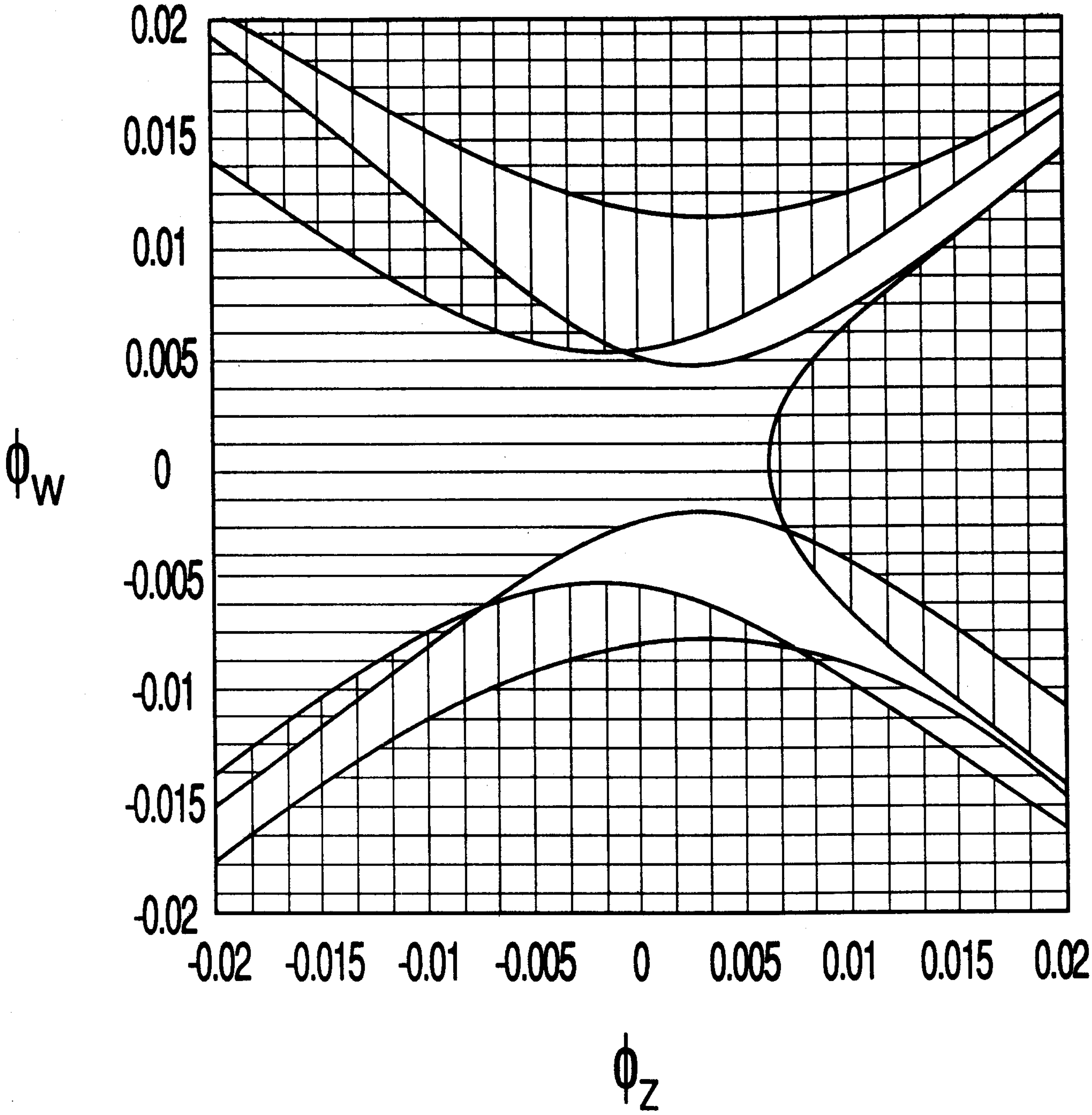
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Figure 2