We propose an extension of the Standard Model by extending the EW symmetry to $SU(2)_L \times U(1) \times Z_2$ and introducing three $SU(2) \times U(1)$ singlet right handed neutrinos, $N_R$, and an additional Higgs doublet, $\phi$. While the SM gauge bosons and the quarks and charged leptons acquire masses from the spontaneous breaking of $SU(2)_L \times U(1)$ symmetry at the electroweak scale, the neutrinos acquire masses from the spontaneous breaking of the discrete $Z_2$ symmetry at a scale of $10^{-2}$ eV. In addition to providing a new mechanism for generating tiny masses for the neutrinos, the model has interesting implications for neutrinoless double beta decay and the Higgs signals at high energy colliders, as well as in astrophysics and cosmology.

1 Introduction

All experimental results to date are in excellent agreement with the predictions of the Standard Model (SM). However, one essential ingredient of the SM, the existence of the Higgs boson, as well as the interactions of the Higgs boson with the SM particles, are yet to be experimentally established. In the SM, we have only one Higgs doublet, and its interactions with the gauge bosons and fermions are completely determined by theory. However, there are several extensions of the SM Higgs sector which include more than one electroweak (EW) doublet, as well as EW singlets [1]. Such extensions include the Minimal Supersymmetric Standard Model (MSSM) which requires two EW Higgs doublets, and the Next to Minimal Supersymmetric Standard Model (NMSSM) which has two doublets and one singlet, as well as models with more than one singlet [2]. There are also non-supersymmetric two Higgs doublet models. Typically, all these extensions involve new additional parameters, and as a result, are not as predictive as the SM for the interactions of the Higgs bosons with the SM gauge bosons and fermions.

Although the mass of the Higgs boson is not predicted by the SM, accurate measurements of the top quark and the $W$ boson mass at the Tevatron, as well as the $Z$ boson mass at LEP,
have narrowed the SM Higgs boson mass between 80 and 200 GeV [3]. Failure to observe the SM Higgs boson at LEP2 has also placed a direct lower bound of 114 GeV on its mass [4]. The dominant decay modes of the SM Higgs boson are to $b\bar{b}$, $WW$, $ZZ$ or $t\bar{t}$, depending on its mass. The extensions of the SM may avoid constraints on the Higgs mass, and may allow Higgs bosons with masses less than the above limits. The dominant decay modes of the Higgs bosons can also be altered in such extensions, thus transforming the discovery signals for the Higgs bosons at the Large Hadron Collider (LHC).

Another fundamental question is how the SM neutrinos acquire tiny masses that are almost a billionth times smaller than the quark and charged lepton masses and whether the neutrinos are Majorana or Dirac particle. The most popular explanation of the tiny neutrino masses is the sea-saw mechanism [5] which invokes the existence of a very heavy EW singlet ($\sim 10^{14}$ GeV) right-handed neutrino. Although there are several indirect benefits of its existence, there is no direct experimental evidence for such a heavy particle. It is important to explore other possibilities to explain the tiny neutrino masses [6].

In this work, we present an alternate explanation for the tiny masses of the SM neutrinos, as well as possibilities for altering signals for discovery of the Higgs at the LHC. Our proposal is to extend the SM electroweak symmetry to $SU(2)_L \times U(1) \times Z_2$ and introduce three $SU(2) \times U(1)$ singlet right handed neutrinos, $N_R$, as well as an additional Higgs doublet, $\phi$. While the SM symmetry is spontaneously broken by the VEV of an EW doublet $\chi$ at the 100 GeV scale, the discrete symmetry $Z_2$ is spontaneously broken by the tiny VEV of this additional doublet $\phi$ at a scale of $10^{-2}$ GeV. Thus in our model, tiny neutrino masses are related to this $Z_2$ breaking scale. We note that although our model has extreme fine tuning, that is no worse than the fine tuning problem in the usual GUT model. Many versions of the two Higgs doublet model have been extensively studied in the past [1]. The examples include: a) a supersymmetric two Higgs doublet model, b) non-supersymmetric two Higgs doublet models i) in which both Higgs doublets have vacuum expectation values (VEV’s) with one doublet coupling to the up type quarks only, while the other coupling to the down type quarks only, ii) only one doublet coupling to the fermions, and iii) only one doublet having VEV’s and coupling to the fermions [7]. What is new in our model is that one doublet couples to all the SM fermions except the neutrinos, and has a VEV which is same as the SM VEV, while the other Higgs doublet couples only to the neutrinos with a tiny VEV $\sim 10^{-2}$ eV. This latter involves the Yukawa coupling of the left-handed SM neutrinos with a singlet right-handed neutrino, $N_R$. The left-handed SM neutrinos combine with the singlet right-handed neutrinos to make massive Dirac neutrinos. The neutrino mass is so tiny because of the tiny VEV of the second Higgs doublet, which is responsible for the spontaneous breaking of the discrete symmetry, $Z_2$. Note that in the neutrino sector, our model is very distinct from the sea-saw model. Lepton number is strictly conserved, and hence no $N_R^cN_R$ mass terms are allowed. Thus the neutrino is a Dirac particle, and there is no neutrinoless double $\beta$ decay in our model. In the Higgs sector, in addition to the usual massive neutral scalar and pseudoscalar Higgs, and two charged Higgs, our model contains one essentially massless scalar Higgs. We will show that this is still allowed by the current experimental data and can lead to an invisible decay mode of the SM-like Higgs boson, thus complicating the Higgs searches at the Tevatron and the LHC.
2 Model and the Formalism

Our proposed model is based on the symmetry group $SU(3)_c \times SU(2)_L \times U(1) \times Z_2$. In addition to the usual SM fermions, we have three EW singlet right-handed neutrinos, $N_R i, i = 1 - 3$, one for each family of fermions. The model has two Higgs doublets, $\chi$ and $\phi$. All the SM fermions and the Higgs doublet $\chi$, are even under the discrete symmetry, $Z_2$, while the RH neutrinos and the Higgs doublet $\phi$ are odd under $Z_2$. Thus all the SM fermions except the left-handed neutrinos, couple only to $\chi$. The SM left-handed neutrinos, together with the right-handed neutrinos, couple only to the Higgs doublet $\phi$. The gauge symmetry $SU(2) \times U(1)$ is broken spontaneously at the EW scale by the VEV of $\chi$, while the discrete symmetry $Z_2$ is broken by a VEV of $\phi$, and we take $\langle \phi \rangle \sim 10^{-2} \text{eV}$. Thus, in our model, the origin of the neutrino masses is due to the spontaneous breaking of the discrete symmetry $Z_2$. The neutrinos are massless in the limit of exact $Z_2$ symmetry. Through their Yukawa interactions with the Higgs field $\phi$, the neutrinos acquire masses much smaller than those of the quarks and charged leptons due to the tiny VEV of $\phi$.

The Yukawa interactions of the Higgs fields with the leptons are

$$L_Y = y_l \overline{\Psi}_L^t l_R^i \chi + y_\nu \overline{\Psi}_L^t N_R^i \tilde{\phi} + \text{h.c.}, \quad (1)$$

where $\overline{\Psi}_L^t = (\overline{\nu}_l, \overline{\ell})_L$ is the usual lepton doublet and $l_R$ is the charged lepton singlet. The first term gives rise to the mass of the charged leptons, while the second term gives a tiny neutrino mass. The interactions with the quarks are the same as in the Standard Model with $\chi$ playing the role of the SM Higgs doublet. Note that in our model, a SM left-handed neutrino, $\nu_L$, combines with a right handed neutrino, $N_R$, to make a massive Dirac neutrino with a mass $\sim 10^{-2} \text{eV}$, the scale of $Z_2$ symmetry breaking.

For simplicity, we do not consider CP violation in the Higgs sector. (Note that in this model, spontaneous CP violation would be highly suppressed by the small VEV ratio and could thus be neglected. However, one could still consider explicit CP violation). The most general Higgs potential consistent with the $SM \times Z_2$ symmetry is [8]

$$V = -\mu_1^2 \chi^\dagger \chi - \mu_2^2 \phi^\dagger \phi + \lambda_1 (\chi^\dagger \chi)^2 + \lambda_2 (\phi^\dagger \phi)^2 + \lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi) - \lambda_4 |\chi^\dagger \phi|^2 - \frac{1}{2} \lambda_5 [(\chi^\dagger \phi)^2 + (\phi^\dagger \chi)^2]. \quad (2)$$

The physical Higgs fields are a charged field $H$, two neutral scalar fields $h$ and $\sigma$, and a neutral pseudoscalar field $\rho$. In the unitary gauge, the two doublets can be written

$$\chi = \frac{1}{\sqrt{2}} \left( \begin{array}{c} \sqrt{2}(V_\phi/V)H^+ \\ h_0 + i(V_\phi/V)\rho + V_\chi \end{array} \right),$$

$$\phi = \frac{1}{\sqrt{2}} \left( \begin{array}{c} -\sqrt{2}(V_\chi/V)H^+ \\ \sigma_0 - i(V_\chi/V)\rho + V_\phi \end{array} \right), \quad (3)$$

where $V_\chi = \langle \chi \rangle$, $V_\phi = \langle \phi \rangle$, and $V^2 = V_\chi^2 + V_\phi^2$. The particle masses are
\[ m_W^2 = \frac{1}{4} g^2 V^2, \quad m_H^2 = \frac{1}{2} (\lambda_4 + \lambda_5) V^2, \quad m_\rho^2 = \lambda_5 V^2, \]

\[ m_{h,\sigma}^2 = (\lambda_1 V_\chi^2 + \lambda_2 V_\phi^2) \pm \sqrt{(\lambda_1 V_\chi^2 - \lambda_2 V_\phi^2)^2 + (\lambda_3 - \lambda_4 - \lambda_5)^2 V_\chi^2 V_\phi^2}, \]  \hspace{1cm} (4)

An immediate consequence of the scenario under consideration is a very light scalar \( \sigma \) with mass

\[ m_\sigma^2 = 2 \lambda_2 V_\phi^2 [1 + O(V_\phi/V_\chi)]. \]  \hspace{1cm} (5)

The mass eigenstates \( h, \sigma \) are related to the weak eigenstates \( h_0, \sigma_0 \) by

\[ h_0 = c h + s \sigma, \quad \sigma_0 = -s h + c \sigma, \]  \hspace{1cm} (6)

where \( c \) and \( s \) denotes the cosine and sine of the mixing angles, and are given by

\[ c = 1 + O(V_\phi^2/V_\chi^2), \]

\[ s = -\frac{\lambda_3 - \lambda_4 - \lambda_5}{2\lambda_1}(V_\phi/V_\chi) + O(V_\phi^2/V_\chi^2). \]  \hspace{1cm} (7)

Since \( V_\phi \sim 10^{-2} \) eV and \( V_\chi \sim 250 \) GeV, this mixing is extremely small, and can be neglected. Hence, we see that \( h \) behaves essentially like the SM Higgs (except of course in interactions with the neutrinos).

The interactions of the neutral Higgs fields with the \( Z \) are given by

\[ L_{gauge} = \frac{g}{2V} (cV_\phi + sV_\chi)(\rho \partial^\mu h - h \partial^\mu \rho)Z_\mu + \frac{\tilde{g}}{2V} (sV_\phi - cV_\chi)(\rho \partial^\mu \sigma - \sigma \partial^\mu \rho)Z_\mu \]

\[ + \frac{\tilde{g}^2}{4} (sV_\phi - cV_\chi)hZ^\mu Z_\mu + \frac{\tilde{g}^2}{4} (cV_\phi + sV_\chi)\sigma Z^\mu Z_\mu + \frac{\tilde{g}^2}{8} (h^2 + \sigma^2 + \rho^2)Z^\mu Z_\mu \]  \hspace{1cm} (8)

where \( \tilde{g}^2 = g^2 + g'^2 \), and \( V_\chi \) and \( V_\phi \) are the two VEV’s.

### 3 Phenomenological Implications

We now consider the phenomenological implications of this model. There are several interesting phenomenological implications which can be tested in the upcoming neutrino experiments and high energy colliders. The light neutrinos in our model are Dirac particles. So neutrinoless double beta decay is not allowed in our model. This is a very distinctive feature
of our model for the neutrino masses compared to the traditional see-saw mechanism. In
the see-saw model, light neutrinos are Majorana particles, and thus neutrinoless double beta
decline is allowed. The current limit on the double beta decay is $m_{ee} \sim 0.3 \text{ eV}$. This limit is
expected to go down to about $m_{ee} \sim 0.01 \text{ eV}$ in future experiments [9]. If no neutrinoless
double beta decay is observed to that limit, that will cast serious doubts on the see-saw
model. In our model, of course, it is not allowed at any level.

Next, we consider the implications of our model for high energy colliders. First we
consider the production of the light scalar $\sigma$ in $e^+e^-$ collisions. The only possible decay
modes of this particle are a diphoton mode, $\sigma \rightarrow \gamma\gamma$ which can occur at the one-loop
level and, if it has enough mass, a $\sigma \rightarrow \nu\nu$ mode. The one loop decay to two photons
takes place with quarks, $W$ bosons, or charged Higgs bosons in the loop. The largest
contribution to this decay mode is $\sim e^8 m_\sigma^5/m_q^4$. This gives the lifetime of $\sigma$ to be $\sim 10^{20}$
years, which is much larger than the age of the universe. Thus $\sigma$ essentially behaves like
a stable particle, and its production at the colliders will lead to missing energy in the
event. The couplings of $\sigma$ to quarks and charged leptons take place only through mixing
which is highly suppressed (proportional to the ratio $V_{\phi}/V_\chi$). Thus we need only consider
its production via its interactions with gauge bosons. The $ZZ\sigma$ coupling is also highly
suppressed, so that processes such as $e^+e^- \rightarrow Z^* \rightarrow Z\sigma$ and $Z \rightarrow Z^*\sigma \rightarrow f\bar{f}\sigma$ are negligible.
However, no such suppression occurs for the $ZZ\sigma\sigma$ coupling. Consider the $Z$ decay process
$Z \rightarrow Z^*\sigma\sigma \rightarrow f\bar{f}\sigma\sigma$. A direct calculation yields the width (neglecting the $\sigma$ and fermion
masses),

$$
\Gamma(Z \rightarrow f\bar{f}\sigma\sigma) = \frac{G_F^3 m_Z^5 (g_V^2 + g_A^2)}{2\sqrt{2}(2\pi)^5} \int_0^{m_Z/2} dE_1 \int_0^{m_Z/2} dE_2 \\
\times \int_{-1}^1 d(\cos \theta) \frac{E_1^2 E_2^2 (3 - \cos \theta)}{(2E_1 E_2 - 2E_1 E_2 \cos \theta - m_Z^2)^2 + m_\rho^2 \Gamma_Z^2},
$$

(9)

where $g_V = T_3 - 2Q \sin^2 \theta_W$ and $g_A = T_3$. This gives

$$
\sum_f \Gamma(Z \rightarrow f\bar{f}\sigma\sigma) \approx 2.5 \times 10^{-7} \text{ GeV}.
$$

(10)

For the $1.7 \times 10^7 \text{ Z's}$ observed at resonance at LEP1 [10], this gives an expectation of only
about two such events.

Now we consider the production of the heavy Higgs particles in our model. Since the
charged Higgs $H^\pm$ and the pseudoscalar, $\rho$ can be produced along with the light scalar $\sigma$, there
will be stricter mass bound on these particles than in a typical two Higgs doublet
model. Let us consider the pseudoscalar $\rho$, and assume $m_\rho < m_Z$. Then the $Z$ can decay via
$Z \rightarrow \sigma\rho$. Since $\rho$ couples negligibly to all SM fermions except the neutrinos, here we need
only consider its decay to $\nu\sigma$ (or $\sigma\sigma$ if we consider CP violation), so this process contributes
to the invisible decay width of the $Z$. The width for this process is

$$
\Gamma = \frac{G_F m_\rho}{24\sqrt{2}\pi} \left(1 - \frac{m_\rho^2}{m_Z^2}\right)^3
$$

(11)
This is less than the experimental uncertainty in the invisible $Z$ width for $m_\rho \gtrsim 78$ GeV. (The experimental value of the invisible $Z$ width is $499.0 \pm 1.5$ MeV [III].)

For $m_\rho > m_Z$, real pseudoscalar $\rho$ can be produced via $e^+e^- \to Z^* \to \rho \sigma$. The total cross section for this process is

$$\sigma = \frac{G_F^2 m_Z^4 (g_V^2 + g_A^2) s}{24\pi} \left( \frac{1}{s - m_Z^2} \right)^2 \left( 1 - \frac{m_\rho^2}{s} \right)^3. \quad (12)$$

For LEP2, $\sqrt{s} \approx 200$ GeV, we find that less than one event is expected in $\simeq 3000$ pb$^{-1}$ [4] of data for $m_\rho \gtrsim 95$ GeV. Note that the bound on the $\rho$ mass we obtain is much less than the mass for which the Higgs potential becomes strongly coupled ($\lambda_5 \leq 2\sqrt{\pi}$ which gives $m_\rho \lesssim 470$ GeV).

For $m_\rho > m_Z$, the $Z$ can still decay invisibly through $Z \to \rho^* \sigma \to \nu \bar{\nu} \sigma \sigma$. The width for this decay is

$$\Gamma = \frac{G_F m_Z^2 y_{\nu_1}^2}{3\sqrt{2}(2\pi)^3} \int_0^{m_Z/2} dE \frac{E^3 (m_Z - 2E)}{(m_Z^2 - 2m_Z E - m_\rho^2)^2}. \quad (13)$$

Summing over generations, this gives

$$\Gamma(m_\rho = 100 \text{ GeV}) \simeq (0.1 \text{ MeV})(\frac{1}{3} \sum_l y_{\nu_l}^2)$$

$$\Gamma(m_\rho = 200 \text{ GeV}) \simeq (4 \times 10^{-3} \text{ MeV})(\frac{1}{3} \sum_l y_{\nu_l}^2). \quad (14)$$

Even if we take $\frac{1}{3} \sum_l y_{\nu_l}^2 \sim 1$, these values are well within the experimental uncertainty in the invisible $Z$ width of 1.5 MeV. Note that if we allow explicit CP violation in the Higgs sector, the invisible decay $Z \to \rho \sigma \to \sigma \sigma$ will also occur.

Our model has very interesting implications for the discovery signals of the Higgs boson at the high energy colliders, such as the Tevatron and LHC. Note that since $V_\phi$ is extremely small compared to $V_\chi$, the neutral Higgs boson, $h$ is like the SM Higgs boson so far its decays to fermions and to $W$ and $Z$ bosons are concerned. However, in our model, $h$ has new decay modes, such as $h \to \sigma \sigma$ which is invisible. This could change the Higgs signal at the colliders dramatically. The width for this invisible decay mode $h \to \sigma \sigma$ is given by

$$\Gamma(h \to \sigma \sigma) = \frac{(\lambda_3 + \lambda_4 + \lambda_5)^2 V_\chi^2}{32\pi m_h}. \quad (15)$$

Using

$$m_h^2 = 2\lambda_1 V_\chi^2 + O(V_\phi^2/V_\chi^2), \quad (16)$$

6
Figure 1: Left panel: Branching ratio for $h \to \sigma \sigma$ as a function of $m_h$ for the value of the parameter, $\lambda^* = 0.1$. Right panel: Branching ratio for $h \to \sigma \sigma$ as a function of $\lambda^*$ for $m_h = 135$ GeV.

This can be written

$$\Gamma(h \to \sigma \sigma) = \frac{(\lambda_3 + \lambda_4 + \lambda_5)^2 m_h}{64\pi \lambda_1}. \quad (17)$$

Depending on the parameters, it is possible for the dominant decay mode of $h$ to be this invisible mode. The branching ratios for the Higgs decay to this invisible mode are shown in fig. 1 (left panel), for the Higgs mass range from 100 to 300 GeV, for the choice of the value of the parameter, $\lambda^*$ equal to 0.1 where $\lambda^*$ is defined to be equal to $\frac{(\lambda_3 + \lambda_4 + \lambda_5)^2}{\lambda_1}$. Right panel in Fig. 1 shows how this branching ratio depends on this parameter for a Higgs mass of 135 GeV. (The results for the branching ratio is essentially the same for other values of the Higgs mass between 120 and 160 GeV). We see that for a wide range of this parameter, for the Higgs mass up to about 160 GeV, the invisible decay mode dominates, thus changing the Higgs search strategy at the Tevatron run 2 and the LHC. The production rate of the neutral scalar Higgs $h$ in our model are essentially the same as in the SM. This implies that the Higgs mass bound from LEP is not significantly altered. (The L3 collaboration set a bound of $m_h \geq 112.3$ GeV for an invisibly decaying Higgs with the SM production rate [12]). However, because of the dominance of the invisible decay mode, it will be very difficult to observe a signal at the LHC in the usual production and decay channels such as $qqh \to qqWW$, $qqh \to q\tau\tau$, $h \to \gamma\gamma$, $h \to ZZ \to 4l$, $t\bar{t}h$ (with $h \to b\bar{b}$) and $h \to WW \to l\nu l\nu l\nu$ [13]. However, a signal with such an invisible decay mode of the Higgs (as in our model) can be easily observed at the LHC through the weak boson fusion processes, $qq \to qqW^+W^- \to qqH$ and $qq \to qqZZ \to qqH$ [14] if appropriate trigger could be designed for the ATLAS and CMS detector. For example, with only $10 fb^{-1}$ of data at the LHC, such a signal can be observed at the 95 percent CL with an invisible branching ratio of 31 percent or less for a Higgs mass of up to 400 GeV [14]. Thus our model can be easily tested at the LHC for a large region of the Higgs mass. Of course, establishing that this signal is from the Higgs boson production will be very difficult at the LHC. For the Higgs search at the Tevatron, the usual signal from the $W h$ production, and the subsequent decays of $h$ to $WW^*$ or $b\bar{b}$ will be absent. The most promising mode in our model will be the production of $ZH$, with
Z decaying to $l^\pm l^\pm$ ($l = e, \mu$) and the Higgs decaying invisibly. There will be a peak in the missing energy distribution in the final state with a Z. We urge the Tevatron collaborations to look for such a signal.

Our model has several interesting astrophysical and cosmological implications. The scalar particle, $\sigma$ in our model is extremely light, with mass $\sim 10^{-2} - 10^{-3}$ eV, but its coupling to $\nu\overline{\nu}$ is unsuppressed. This new interaction will affect supernova explosion dynamics. Also, since this interaction $\nu\overline{\nu}\sigma$ can be pretty strong, it can bound $\nu\overline{\nu}$ giving rise to $\nu\overline{\nu}$ atoms, thus giving rise to the possibility of new kind of star formation. The spontaneous breaking of the discrete global symmetry, $Z_2$ will lead to cosmological domain walls. It will be interesting to see it can contribute to the vacuum energy in a significant way. The scalar field, $\sigma$ in our model has also mass in the right ballpark as the measured value of the cosmological constant, and it is stable on a cosmological time scale. It will be interesting to see if it can be a viable candidate for the dark energy.

4 Conclusions

We have presented a simple extension of the Standard Model supplemented by a discrete symmetry, $Z_2$. We have also added three right-handed neutrinos, one for each family of fermions, and one additional Higgs doublet. While the electroweak symmetry is spontaneously broken at the usual 100 GeV scale, the discrete symmetry, $Z_2$ remains unbroken to a scale of about $10^{-2}$ eV. The spontaneous breaking of this $Z_2$ symmetry by the VEV of the second Higgs doublet generates tiny masses for the neutrinos. The neutrinos are Dirac particles in our model, so the neutrinoless double beta decay is absent. This is a very distinctive feature of our model for neutrino mass generation compared to the usual see-saw model. The neutral heavy Higgs in our model is very similar to the SM Higgs in its couplings to the gauge bosons and fermions, but it also couples to a very light scalar Higgs present in our model. This light scalar Higgs, $\sigma$, is essentially stable, or decays to $\nu\overline{\nu}$. Thus the production of this $\sigma$ at the high energy colliders leads to missing energy. The SM-like Higgs, for a mass up to about 160 GeV dominantly decays to the invisible mode $h \rightarrow \sigma\sigma$. Thus the Higgs signals at high energy hadron colliders are dramatically altered in our model. Our model also has interesting implications for astrophysics and cosmology.

Acknowledgments

We thank K.S. Babu for useful discussions. We also thank D. Rainwater for a very useful communication regarding the observability of the Higgs signals in the presence of an invisible decay mode. This work was supported in part by the US Department of Energy, Grant Numbers DE-FG02-04ER41306 and DE-FG02-04ER46140.
References

[1] See for example, *Higgs Hunters Guide*, by J.F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, Addison-Wesley Publishing, New York, 1990.

[2] See for example, U. Elwanger, J.F. Gunion and C. Hugonie, JHEP **0502** (2005) 066; V.Barger, P. Langacker, H.-S. Lee and G. Shaughnessy, Phys. Rev. **D73** (2006) 115010; R. Schabinger and J. Wells, Phys. Rev. **D72** (2005) 093007; I. Gogoladze, Y. Mimura, T. Li and S. Nandi, Phys. Rev. **D72** (2005) 055006.

[3] LEP EW Working Group, [http://lepewwg.web.cern.ch/LEPEWWG/](http://lepewwg.web.cern.ch/LEPEWWG/).

[4] ALEPH, DELPHI, L3, and OPAL Collaborations, The LEP working group for Higgs boson searches, G. Abbiendi et al., Phys. Lett. **B565** (2003) 61.

[5] P. Minkowski, Phys. Lett. **B67** (1977) 421; M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity* (P. van Nieuwenhuizen et al. eds.), North Holland, Amsterdam, 1980, p. 315; T. Yanagida, in *Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe* (O. Sawada and A. Sugamoto, eds.), KEK, Tsukuba, Japan, 1979, p. 95; S. L. Glashow, in *Proceedings of the 1979 Cargèse Summer Institute on Quarks and Leptons* (M. Levy et al. eds.), Plenum Press, New York, 1980, pp. 68771; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** (1980) 912.

[6] K.R. Dienes, E. Dudas and T. Gherghetta, Nucl. Phys. **B557** (1999) 25; N. Arkani-Hamed, S. Dimopoulos, G. Dvali and J. March-Russell, Phys. Rev. **D65** (2002) 024032; S. Nandi and C.M. Rujoiu, hep/ph/0603243; S. Nandi and U. Sarkar, Phys. Rev. Lett. **56** (1986) 564.

[7] R. Barbieri, L.J. Hall, and V.S. Rychkov, Phys. Rev. **D74** (2006) 015007.

[8] S. Nandi, Phys. Lett. **B202** (1988) 385, Erratum-ibid, **B207** (1988) 520.

[9] L. Baudis et al. Phys. Rev. Lett. **83** (1999) 41; IGEX Collaboration, C.E. Aalseth et al., Phys. Rev. **D65** (2002) 092007; I. Abd et al., hep-ex/0404039.

[10] ALEPH, DELPHI, L3, and OPAL Collaborations, The LEP EW working group, The SLD EW and heavy flavour groups, Phys. Rept. **427** (2006) 257.

[11] W.-M. Yao et al., J. Phys. **G33** (2006) 1.

[12] L3 Collaboration, P. Achard et al., Phys. Lett. **B609** (2005) 35.

[13] K. Crammer, B. Mellado, W. Quayle, and S. L. Wu, (ATLAS Collaboration), ATL-PHYS-2004-034.

[14] O.J.P. Eboli and D. Zepppenfeld, Phys. Lett. **B495** (2000) 147.