Abstract

The large hadron collider experiments have now reached the focus point region in which the scalar masses are multi-TeV. We study the parameter region of the focus point scenario which may realize a natural electroweak symmetry breaking avoiding serious fine tuning. We show that the region with a mild tuning of $3 - 5\%$ level is expanded by introducing right-handed neutrinos in the framework of the seesaw scenario. We discuss the prediction of the Higgs mass, bounds on the squark and gluino masses, and the relic density of the lightest neutralino in such a parameter region.
1 Introduction

The low energy supersymmetry (SUSY) is one of the leading candidates for physics beyond the standard model. In the SUSY models, the quadratic divergence in the Higgs mass squared term disappears and the electroweak symmetry breaking scale is arising from SUSY breaking parameters and SUSY Higgs mass parameter, $\mu$. Thus, it is plausible that the SUSY particles will be discovered around the electroweak symmetry breaking scale. However, the LHC experiments recently reported strong lower bounds on masses of SUSY particles \[1, 2\]. For instance, the gluino and squarks lighter than 1 TeV was already excluded if their masses are nearly equal. Such a LHC bound imposes a serious fine tuning problem to SUSY models.

With the tension between the LHC bound on the masses of superparticles and fine tuning being given, the focus point scenario \[3, 4, 5\] is one of the interesting possibilities to consider. (See also \[6\].) In the focus point region, although scalar masses are multi-TeV, the value of the up-type soft SUSY breaking Higgs mass squared, $m_{H_u}^2$, is around electroweak scale squared due to the “focus point” behavior of the $m_{H_u}^2$ running; consequently the electroweak symmetry breaking may be naturally realized by small $m_{H_u}^2$ and $\mu$ parameters. In the multi-TeV scalar mass region, the lower bound on the gluino mass is relaxed and it is about 600 GeV. Thus, in focus point scenario, a mild tuning of parameters may be enough to realize the electroweak symmetry breaking without conflicting the LHC bounds.

As we see below, however, the Higgs mass bound from the LEP experiment ($m_h \geq 114.4$ GeV \[7\]) also puts serious constraint on the parameter space. In particular, a large fraction of the parameter region with a tuning of a few % is excluded by the Higgs mass constraint if we adopt the particle content of the minimal supersymmetric standard model (MSSM).

One of the plausible extension of the MSSM is to introduce heavy right-handed neutrinos. Even if the neutrino Yukawa coupling is $\mathcal{O}(1)$, the small neutrino mass can be explained by the seesaw mechanism \[8, 9, 10\] with the large Majorana mass of the right-handed neutrino. The purpose of this letter is to show that if the Yukawa coupling of a neutrino is $\mathcal{O}(1)$, the allowed parameter space in the focus point region significantly expands and we have a large region of mild tuning. In particular, we show that a parameter region with $3 - 5 \%$ tuning is allowed in the focus point region where multi-TeV scalars exist.

2 Focus point scenario without seesaw

First, we briefly summarize how the focus point region is constrained by various experimental bounds in the framework of the MSSM.

In the MSSM, the electroweak symmetry breaking scale is given by the SUSY Higgs mass parameter, $\mu$, and soft SUSY breaking masses as

$$\frac{1}{2} m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} \sim -\mu^2 - m_{H_u}^2, \quad (1)$$
where \( m^2_{H_u} (m^2_{H_d}) \) is the up- (down-) type soft SUSY breaking Higgs mass squared at the electroweak scale and \( \tan \beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle \). The last relation holds for a moderately large value of \( \tan \beta \) and the relation can be rewritten by the following form:

\[
\frac{1}{2} m^2_Z \sim - \mu^2 - m^2_{H_u} |_{\text{mess}} - \delta m^2_{H_u},
\]

(2)

where the \( m^2_{H_u} |_{\text{mess}} \) is the up-type Higgs mass at the SUSY breaking mediation scale and \( \delta m^2_{H_u} \) denotes the contribution of the running from the mediation scale to the electroweak scale. In naive discussion, naturalness requires that each term in the right-hand side should not be much larger than the electroweak symmetry breaking scale. This requires that the masses of scalar top quarks (stops) should not be much larger than the electroweak scale in order for the electroweak symmetry breaking to naturally happen (for details of the naturalness bound on stop mass, see, for e.g., [11, 12, 13]).

The above conclusion may change in the focus point region. To see this, we study the running of MSSM parameters in the framework of the minimal supergravity (mSUGRA) with the following input parameters:

\[
(m_0, m_{1/2}, A_0, B_0, \mu),
\]

where \( m_0, m_{1/2}, A_0 \) and \( B_0 \) are the universal scalar mass, gaugino mass, tri-linear coupling and the dimensionful Higgs mixing parameter at the grand unified theory (GUT) scale \( M_{\text{GUT}} \), respectively. Notice that \( B_0 \) is determined once the low energy parameter \( \tan \beta \) (as well as other GUT scale parameters) is fixed. In mSUGRA, eq. (2) becomes

\[
\frac{1}{2} m^2_Z \sim - \mu^2 - c_0 m_0^2 - c_{1/2} m_{1/2}^2 - c_A A_0^2 - c_{Am}(m_{1/2} A_0),
\]

(3)

where the coefficients \( c_0, c_{1/2}, c_A \) and \( c_{Am} \) are determined once the gauge and Yukawa coupling constants, \( M_{\text{GUT}} \), and \( \tan \beta \) are given. The focus point mechanism works if \( c_0 \) is much smaller than 1 [14, 15, 16, 14, 15]; in such a case, \( m^2_{H_u} \) at the electroweak scale is insensitive to \( m_0 \) because the focus scale of the \( m^2_{H_u} \) running becomes close to the electroweak scale. This means the electroweak scale also becomes insensitive to the parameter \( m_0 \), so \( m_0 \) (i.e., typical scalar masses) can be multi-TeV without conflicting with the fine tuning constraint. Using the GUT scale and top quark mass suggested by experimental data, it is well known that the value of \( c_0 \) is relatively small. Notice that, on the contrary, \( m_{1/2}, A_0 \) and \( \mu \) should not be much larger than the electroweak scale for the naturalness.

In the actual situation, however, the Higgs mass bound imposes a serious constraint on such a scenario. This is because a large value of the stop mass is required to enhance the lightest Higgs mass, which conflicts with the naturalness bound. In Fig. 1, we show the contours of constant Higgs mass on \( m_0 \) vs. \( m_{1/2} \) plane, as well as the fine tuning parameter defined as [17, 14]

\[
\Delta_a \equiv \frac{\partial \ln m^2_Z}{\partial \ln a},
\]

(4)
with

\[ a = (m_0, m_{1/2}, A_0, B_0, \mu) . \]  

(5)

Notice that \( \Delta \) parametrizes the sensitivity of the electroweak scale to the high scale model parameters. In the same figure, we also show contours of constant chargino and gluino masses. In addition, we also draw the contour on which the thermal relic abundance of the lightest neutralino is consistent with the WMAP value \( \Omega_c h^2 = 0.112 \) [18]. In our analysis, we take \( \tan \beta = 10 \) and 30, \( M_{\text{GUT}} = 2 \times 10^{16} \text{ GeV} \), and the top quark mass is taken to be \( m_t = 173 \text{ GeV} \). The renormalization group evolution and SUSY mass spectrum are calculated by using ISAJET 7.81 [19] #1. In addition, the lightest Higgs mass and the relic abundance are calculated by FeynHiggs 2.8.5 [20] and DarkSUSY 5.0.5 [21], respectively.

In Fig. 1, the green shaded region is excluded by the chargino mass limit from LEP experiments [22]. (Notice that the green region also includes the parameter region where \( m_{H_u}^2 \) becomes positive, resulting in the failure of radiative electroweak symmetry breaking.) On the other hand, the fine tuning parameter \( \Delta \) is mostly determined by \( m_{1/2} \) and \( \mu \) when \( m_{1/2} \) is large or by \( m_0 \) in large \( m_0 \) region. Then, even in focus point region, there exists an upper bound on \( m_0 \) (and hence on the scalar masses) once an upper bound on \( \Delta \) is imposed. Such a naturalness bound contradicts with the Higgs mass bound as seen in Fig. 1. For example, if we take \( \Delta \lesssim 20 \), which corresponds to \( \sim 5 \% \) tuning of the parameters for the electroweak symmetry breaking, the allowed region consistent with the Higgs mass constraint is found to be quite small even for \( \tan \beta = 30 \). In the following, we see how this changes once the right-handed neutrinos are introduced.

### 3 The focus point scenario with seesaw

One of the plausible extension of the MSSM is to introduce right-handed neutrinos in order to explain the small neutrino mass by seesaw mechanism. Then, the renormalization group running of \( m_{H_u}^2 \) is affected by the neutrino Yukawa coupling constants, and the focus point behavior may change [23].

In the seesaw scenario, the active neutrino mass matrix is given by

\[ [m_{\nu L}]_{ij} = \frac{1}{2} \langle H_u^0 \rangle^2 \sum_{kl} [Y_\nu]_{ik} [Y_\nu]_{jl} [\mathcal{M}_{\nu R}]^{-1}_{kl} , \]  

(6)

where \( Y_\nu \) and \( \mathcal{M}_{\nu R} \) are the neutrino Yukawa matrix and the Majorana mass matrix of right-handed neutrinos, respectively. (The indices \( i, j, \cdots \) run 1 \(-\) 3.) Notice that, using the Maki-Nakagawa-Sakata (MNS) matrix \( V_{\text{MNS}} \) [24], \( m_{\nu L} \) is expressed as \( m_{\nu L} = V_{\text{MNS}} \tilde{m}_{\nu L} V_{\text{MNS}}^T \).

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#1 In ISAJET code, we modified the function \texttt{SSRSGT} which computes the threshold correction of the top Yukawa coupling constant \( y_t \) at the SUSY scale. The original code overestimates this correction, which leads to slightly large \( y_t \) above the SUSY scale. It affects significantly electroweak symmetry breaking condition in large \( m_0 \) region. We checked that modified code is almost consistent with other codes.
Figure 1: Experimental bounds and fine tuning parameter on $m_0$ vs. $m_{1/2}$ plane for $\tan\beta = 10$ (left) and 30 (right) in the framework of the MSSM. Here, we take $A_0 = 0$. The blue lines show contours of fine tuning parameter $\Delta = 100$, 33 and 20 from above. The green shaded region corresponds to the region excluded by the chargino mass limit of 103.5 GeV. The red stripe regions is the region excluded by Higgs mass limit of 114.4 GeV, while red contours are for the Higgs mass of $m_h = 116$ GeV and 118 GeV from below. The black line shows contour of $m_{\tilde{g}} = 600$ GeV and 1 TeV. The turquoise line shows the region where the thermal relic density of the lightest neutralino becomes consistent with the dark matter density suggested by the WMAP $\Omega_c h^2 = 0.112$ [18].

where $\tilde{m}_{\nu_L} = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$ with $m_{\nu_i}$ being masses of active neutrinos. As we will discuss later, the rates of the lepton-flavor violating processes strongly depend on the origin of the MNS matrix.

It can be easily seen that the focus scale of $m_{H_u}^2$ parameter changes if the neutrino Yukawa couplings are $O(1)$. This is because the neutrino Yukawa coupling constant gives negative contribution to $m_{H_u}^2$ (at lower scale). Consequently, the upper bound on $m_0$ from the electroweak symmetry breaking condition shifts to large $m_0$ region. The above statement holds irrespective of the detailed structure of the Yukawa and Majorana mass matrices of neutrinos. So, let us briefly discuss how it happens by adopting universal Majorana mass matrix (i.e., $M_{\nu_R} = \text{diag}(M_{\nu_R}, M_{\nu_R}, M_{\nu_R})$) to make the point clear. (Implication of such a choice to the lepton flavor violation will be discussed later.) Using the active neutrino masses suggested from the neutrino oscillation experiments, the largest eigenvalue of $Y_{\nu}$ becomes $O(1)$ if $M_{\nu_R}$ is around $10^{14}$ GeV. Then, in models with right-handed neutrinos, the renormalization group equation of $m_{H_u}^2$ contains the following term:

$$
\frac{dm_{H_u}^2}{d\log Q} = \left[ \frac{dm_{H_u}^2}{d\log Q} \right]_{\text{MSSM}} + \frac{y_{\nu}^2}{16\pi^2} \left( m_{H_u}^2 + m_{L_3}^2 + m_{N_3}^2 \right) \theta(Q - M_{\nu_R}) + \cdots,
$$

where $Q$ is the renormalization scale, the first term is the MSSM contribution, $y_{\nu}$ is the largest eigenvalue of the neutrino Yukawa matrix, and $m_{L_3}^2$ and $m_{N_3}^2$ are SUSY breaking mass squared of the slepton doublet and right-handed sneutrino which couple to $y_{\nu}$, respectively.
(In the above equation, we omit the contribution of tri-linear coupling, which is irrelevant for our discussion.) Here, for simplicity, we have assumed that the eigenvalues of the neutrino Yukawa matrix is hierarchical and that the contribution of the largest eigenvalue dominates. If \( y_\nu \) is sizable, \( m^2_{H_u}(Q) \) becomes negative at the scale higher than that in the case of the MSSM. Then, the focus scale of \( m^2_{H_u} \) becomes higher compared to the MSSM case, and the region with small \( \Delta \) extends to the region with larger \( m_0 \). In such a region, the Higgs mass constraint can be satisfied because of large stop masses. In addition, the fine tuning parameter \( \Delta \) may be suppressed because, in the parameter region near the chargino mass bound, the \( \mu \)-parameter is small.

In Fig.2, we show the contour of the fine tuning parameter \( \Delta \), as well as experimental (and other) bounds. Here, we take \( A_0 = 0, \tan \beta = 10 \) and \( 30, \) and \( M_{\nu_R} = 2 \times 10^{14} \) GeV. The soft SUSY breaking mass squared of the right-handed sneutrinos are also taken to be \( m^2_{0} \) at the GUT scale. On the contour of the fine tuning parameter, the horizontal line is due to \( \Delta_{M_{1/2}} \) and \( \Delta_{\mu} \) while the (almost) vertical one is from \( \Delta_{m_0} \). It is remarkable that the region with a few \% tuning (i.e, \( \Delta \lesssim 33 \)) becomes larger as we take into account the effect of the neutrino Yukawa coupling constant. In the case of \( M_{\nu_R} = 2 \times 10^{14} \) GeV, \( m_0 \) can be as large as \( \sim 2 \) TeV even if we require \( \Delta < 33 \), which is about 500 GeV larger than the case of the MSSM. This makes the discovery of the squarks at the LHC challenging. Even in such a case, however, it should be noted that a bound on the \( m_{1/2} \) parameter is imposed from the naturalness, which can be converted to the upper bound on the gluino mass. If we require \( \Delta < 33 \) (20), gluino should be lighter than 1 TeV (800 GeV) for the case of \( \tan \beta = 30 \). Thus, for the test of the focus point scenario, search of the gluino signal is important. In the present scenario, it is also notable that the lightest Higgs mass cannot be so heavy. Even adopting the tuning of the level of \( \Delta^{-1} = 1 \% \), the Higgs mass is required to be smaller than about 120 GeV.

In the present case, one may worry about the thermal relic density of the lightest neu-
tralino because we consider the parameter region where the sfermion masses are so heavy that the pair annihilation cross section of the lightest neutralino is extremely suppressed (if the lightest neutralino is Bino-like) [25]. In Fig[2] we also show the contour on which the thermal relic density of the lightest neutralino becomes consistent with the present dark matter density. Notice that, as \(m_{1/2}\) becomes larger, the thermal relic density increases. In the region that we are interested in, i.e., in the region where \(\Delta^{-1} \lesssim \text{a few } \%\), the thermal relic density of the lightest neutralino is found to exceed the present dark matter density. If we assume the standard evolution of the universe, this may cause a problem of the overproduction of the lightest neutralino. The relic density, however, depends on the thermal history as well as on the mass spectrum of SUSY particles. Thus, we do not take this problem seriously. For example, if a sizable amount of entropy is produced after the freeze-out of the lightest neutralino, this problem can be avoided. In addition, if the simple GUT relation among the gaugino masses does not hold, then the lightest neutralino may not be purely Bino. If the lightest neutralino has a sizable Wino or Higgsino component, the thermal relic density of the lightest neutralino can be suppressed. In the scenario of the product-group unification [26], such a situation can be easily realized.

Finally, we comment on the lepton flavor violation. Once we introduce right-handed neutrinos, it inevitably becomes a new source of lepton flavor violations. In particular, even if the slepton mass squared matrix is universal at the GUT scale, the neutrino Yukawa interaction induces off-diagonal elements via renormalization group effect [27]. (For detailed study of the lepton flavor violation processes in supersymmetric model with right-handed neutrinos, see [28, 29].) The most stringent constraint is often from \(\mu \to e\gamma\) process; the current upper bound on the branching ratio of this process is \(\text{Br}(\mu \to e\gamma) < 2.4 \times 10^{-12}\) [30]. Even though the slepton masses are of \(\mathcal{O}(1)\) TeV in the focus point scenario, \(\text{Br}(\mu \to e\gamma)\) may become large because we consider the case that the neutrino Yukawa coupling constants are \(\mathcal{O}(1)\). Importantly, the rates of lepton flavor violating processes strongly depend on the structures of Yukawa and Majorana mass matrices in the neutrino sector. For example, if \(\mathcal{M}_\nu\) is universal, the mixing in the Yukawa matrix should be sizable to realize the mixings of active neutrinos observed. Then, it is often the case that \(\text{Br}(\mu \to e\gamma)\) becomes unacceptably large. Even in such a case, however, \(\text{Br}(\mu \to e\gamma)\) depends on the value of \([V_{\text{MNS}}]_{e3}\), which is presently unknown. If \(|[V_{\text{MNS}}]_{e3}| \ll 1\), \(\text{Br}(\mu \to e\gamma)\) becomes larger than the experimental bound in the region of \(\Delta < 100\). However if \(|[V_{\text{MNS}}]_{e3}| \sim 0.06\), there is a possibility of accidental cancellation so that \(\text{Br}(\mu \to e\gamma)\) is suppressed. Furthermore, if the neutrino mixing is dominantly from \(\mathcal{M}_{\nu_R}\), the situation may change. For example, one may take \([Y_\nu]_{ij} \propto \delta_{ij}\) and \([\mathcal{M}_{\nu_R}]_{ij} \propto [m_{\nu_L}]_{ij}^{-1}\); then the flavor violation is significantly suppressed. This is because the relevant part of the \(\beta\)-function of the SUSY breaking mass squared matrix of slepton is proportional to \([Y_\nu Y_\nu^T]_{ji}\). We have checked that, in such a case, the experimental constraints can be avoided if \(m_0 \gtrsim 1\) TeV in the case that the right-handed neutrino masses are around \(2 \times 10^{14}\) GeV and \(\tan \beta = 10\). More detailed discussion on this issue will be given elsewhere [31].
4 Conclusions and Discussion

In this letter, we have considered the possibility of relaxing the fine tuning constraint using the focus point scenario. We have shown that the focus point parameter space consistent with the serious Higgs mass constraint is expanded by introducing right-handed neutrinos. Due to the contribution from the large Yukawa coupling of the right-handed neutrinos, the naturalness bound on the $m_0$ vs. $m_{1/2}$ plane is changed. Then, we have shown that the parameter space with a few percent tuning becomes significantly larger. We have seen that a parameter space with $\sim 5\%$ tuning even exists with the scalar mass larger than 1 TeV. We have found that, adopting $3\%$ ($5\%$) tuning for the electroweak symmetry breaking, the gluino mass is bounded above as $m_{\tilde{g}} < 1$ TeV (800 GeV).

Finally, we comment on the limit on the gluino mass. In deriving the LHC bound on the gluino mass, the GUT relation among the gaugino masses is usually adopted. Then, the gluino mass is constrained as $m_{\tilde{g}} > 600$ GeV in the focus point region. However, in some class of GUT models, the GUT relation does not always hold; in the unification model based on product groups [26], for example, that is the case [32]. If the masses of gluino and dark matter are quasi-degenerated, bound on the gluino mass may be relaxed [33]. Implications of such a possibility in the focus point scenario (as well as in more general framework) will be discussed elsewhere [31].

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