13 and the Higgs Mass from High-Scale Supersymmetry Postprint

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Abstract

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Full Text

Preamble

θ_{13} and the Higgs mass from high scale supersymmetry

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Abstract

In the framework where supersymmetry is used for understanding fermion masses rather than stabilizing the electroweak scale, we elaborate on the phenomenological analysis for neutrino physics. A relatively large $\sin\theta_{13} \simeq 0.13$ is naturally obtained. The model further predicts vanishingly small CP violation in neutrino oscillations. While high scale supersymmetry generically results in a Higgs mass of about 141 GeV, our model reduces this mass to 126 GeV

via introducing $SU(2)_L$ triplet fields which make the electroweak vacuum metastable (with a safe lifetime) and also contribute to neutrino masses.

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INTRODUCTION

Particle physics currently stands at a crucial stage. Experiments have been pushing the energy frontier, up to which the Standard Model (SM) remains valid, ever higher. In this situation, neutrino experiments deserve increasing attention. Recently, the Daya Bay [?] and RENO [?] experiments have established that θ_{13} is relatively large. This result was earlier indicated by T2K [?], MINOS [?], and Double Chooz [?] experiments, as well as by global fits [?]. This relatively large θ_{13} has important implications for theories addressing the flavor puzzle.

On the theoretical side, the SM still faces problems, such as how to understand the Higgs mass and whether the flavor puzzle can be explained. Lacking new physics signals, the electroweak (EW) scale may simply have an anthropic origin [?, ?]. TeV-scale supersymmetry (SUSY) is losing its motivation. Inspired by the simplicity and beauty of SUSY, one of the authors (Liu) proposed using SUSY to understand the flavor puzzle [?, ?]. In this model, a family symmetry is introduced such that only one generation of fermions acquires masses after electroweak symmetry breaking—specifically, the third generation.

It is SUSY that provides the necessary features to break the family symmetry. For the lepton sector, once sneutrino fields acquire different vacuum expectation values (VEVs), the family symmetry is broken and the muon becomes massive. The electron obtains its mass only through loops due to soft SUSY breaking effects where the family symmetry is explicitly broken. To naturally obtain small neutrino masses, soft SUSY masses should be very large (10^{11}–10^{13} GeV). The effective theory of this high-scale SUSY breaking model at the TeV scale is just the SM.

In this Letter, we emphasize that a relatively large θ_{13} is a natural result of this high-scale SUSY model. Furthermore, the model predicts vanishingly small CP violation in neutrino oscillations. In Ref. [?], an order 0.1 $\sin\theta_{13}$ was roughly predicted, and CP violation in the lepton sector was not discussed. We will elaborate on the phenomenological analysis of neutrino oscillations with better approximation.

More importantly, high-scale SUSY generically predicts the SM Higgs mass to be 141 GeV (for large $\tan\beta$ as in our case) [?], while recent LHC experiments have ruled out this mass and discovered that the Higgs mass is 126 GeV [?]. To reduce the Higgs mass from 141 GeV to about 126 GeV, we utilize an observation from Ref. [?] to modify the model by introducing $SU(2)_L$ triplets at the high scale. These can change the Higgs quartic coupling at the high-energy boundary to be even negative. They also contribute additionally to neutrino masses.

In the next section, we review the basics of the original model. Section III introduces $SU(2)_L$ triplets. Neutrino phenomenology is analyzed in Section IV. The Higgs mass is discussed in Section V. Summary and discussions are given in the final section.

II. REVIEW

Within the framework of SUSY, we introduce a Z_3 cyclic family symmetry among the $SU(2)_L$ lepton doublets L_i ($i = 1, 2, 3$) for three generations. All other fields are trivial representations of this Z_3. It is then convenient to discuss physics in terms of the following redefined fields:

$L'_\tau = (L_1 + L_2 + L_3)/\sqrt{3},\ L'_e = (L_1 + \omega L_2 + \omega^2 L_3)/\sqrt{3},\ L'_\mu = (L_1 + \omega^2 L_2 + \omega L_3)/\sqrt{3},$

where $\omega = e^{2\pi i/3}$. Because L'_τ is invariant under Z_3, in general it mixes with the down-type Higgs H_2.

$L_e L_\mu$ is the only bilinear Z_3-invariant combination of the above fields, which is also an $SU(2)_L$ singlet. The Z_3 and gauge symmetric superpotential is expressed as follows [**?**]:

$W = y_\tau H_d L_\tau E^c_\tau + L_e L_\mu(\lambda_\tau E^c_\tau + \lambda_\mu E^c_\mu) + \bar{\mu} H_u H_d,$

where L_τ and H_d denote the physical τ lepton doublet and the physical down-type Higgs, which are superpositions of L'_τ and H_2. E^c stands for charged lepton singlets, H_u for the up-type Higgs, y_τ and λ's for couplings, and $\bar{\mu}$ for a mass parameter. Consequently, the mass matrix for charged leptons has the following form when Higgs and sneutrinos get VEVs:

$$M_l = \begin{pmatrix} 0 & \lambda_\mu v_{l_\mu} & \lambda_\tau v_{l_\mu} \\ 0 & \lambda_\mu v_{l_e} & \lambda_\tau v_{l_e} \\ y_\tau v_d & 0 & 0 \end{pmatrix}.$$

It can be seen that the τ mass is related to the Higgs VEV, while the muon mass is related to sneutrino VEVs. The electron mass is zero at this stage and will become finite only after SUSY breaking effects are considered [**?**, **?**].

Neutrinos are massive because lepton number is violated. Sneutrino VEVs result in only one nonvanishing neutrino mass in this model:

$$M_\nu = a \begin{pmatrix} v_{l_e} v_{l_e} & v_{l_e} v_{l_\mu} & v_{l_e} v_{l_\tau} \\ v_{l_\mu} v_{l_e} & v_{l_\mu} v_{l_\mu} & v_{l_\mu} v_{l_\tau} \\ v_{l_\tau} v_{l_e} & v_{l_\tau} v_{l_\mu} & v_{l_\tau} v_{l_\tau} \end{pmatrix},$$

where $a = (g^2 + g'^2)/2$, and g and g' are SM gauge coupling constants. A naturally small neutrino mass is obtained by taking the soft SUSY breaking scale $M_{\tilde{m}}$ to be 10^{11}–10^{13} GeV. Note that trilinear R-parity violating terms in this model have negligible contribution to neutrino masses due to large sparticle masses.

The low-energy effective theory is just the SM. Our model is a high-scale SUSY breaking model. In obtaining correct electroweak symmetry breaking, there is a Higgs doublet with its mass-squared finely tuned to be small (the EW scale) and negative, so it gets a non-vanishing EW-scale VEV. In terms of our high-scale fields, the above SM Higgs doublet field generally corresponds to a mixture of scalar fields of H_u, H_d, L_e, L_μ and L_τ in the case of R-parity violation. Equivalently, the scalar fields of H_u, H_d, L_e, L_μ and L_τ have VEVs. The relative sizes of the VEVs are determined by the relative sizes of soft parameters (B_μ terms).

Neutrino oscillation experiments reveal that there are at least two massive neutrinos. To provide realistic neutrino masses, a singlet superfield N was introduced in Ref. [?]. While realistic lepton spectrum and mixing pattern can be obtained, the Higgs mass is still required to be 140 GeV, which is in conflict with recent LHC results.

III. SU(2)L TRIPLETS

Instead of singlet fields, $SU(2)_L$ triplet superfields T and $\bar{T}$ are introduced in this work. T and $\bar{T}$ have hypercharge +2 and -2, respectively, and their mass is about 10^{13} GeV.

The Z_3-invariant superpotential involving T and $\bar{T}$ fields is as follows:

$$W \supset \tilde{y}_\nu \{L_i H_2\} T + \tilde{\lambda}_\nu \{L_i L_i\} T + \lambda_\nu \{H_u H_u\} T + \tilde{y}'_\nu \{H_2 H_2\} \bar{T} + M_T T \bar{T},$$

where $\{L_1 L_2 + L_2 L_3 + L_3 L_1\}$ is understood. The braces denote that the two doublets form an $SU(2)_L$ triplet representation. The Lagrangian of the corresponding soft SUSY breaking terms includes scalar masses and trilinear scalar interactions.

In terms of the redefined fields in Eq. (1), the superpotential has the following form:

$$W = \tilde{y}_\nu \{L_\tau H_d\} T + \lambda_\nu \{L_e L_e + L_\mu L_\mu\} T + \lambda_\nu \{H_u H_u\} T + M_T T \bar{T}.$$

Couplings are denoted without tildes in this flavor basis. In the above derivation, we have made use of the following observation:

$$\{L_e L_e + L_\mu L_\mu\} \propto \{L_i L_i - (L_1 L_2 + L_2 L_3 + L_3 L_1)\} \propto \{L_i L_i + 2(L_1 L_2 + L_2 L_3 + L_3 L_1)\}.$$

In this basis, the Lagrangian of soft SUSY breaking terms is written as:

$$\mathcal{L}_{soft} \supset m_T^2 \tilde{T}^\dagger \tilde{T} + m_{\bar{T}}^2 \tilde{\bar{T}}^\dagger \tilde{\bar{T}} + B_T M_T \tilde{T} \tilde{\bar{T}} + A_{\lambda_\nu} h_u h_u \tilde{\bar{T}} + \tilde{A}_{\lambda_\nu} \{\tilde{l}_a \tilde{l}_b\} \tilde{T} + h.c.,$$

where $\tilde{l}_a$ denotes both sleptons $\tilde{l}_e, \tilde{l}_\mu, \tilde{l}_\tau$ and the Higgs $\tilde{l}_h$ identical to h_d. The soft masses are also taken to be typically about 10^{11}–10^{13} GeV.

Analyzing the scalar potential relevant to T and $\bar{T}$ fields, we see that $\tilde{T}$'s have VEVs. Although being very small, the VEVs induce new terms to the neutrino mass matrix. To be more accurate:

$\langle T\rangle \simeq -(A_{\lambda_\nu} v_u^2 + \tilde{A}_{\lambda_\nu} v_{l_\tau}^2)/M_T^2$, $\langle \bar{T}\rangle \simeq -(B_T M_T)/M_T^2$.

This part of neutrino mass generation is the so-called type-II seesaw mechanism [**?**]. For simplicity, we assume that λ_ν is negligibly small. This smallness can be understood by taking $\tilde{\lambda}_\nu \ll 1$ while $\lambda_\nu \sim 1$. Consequently, the Majorana neutrino mass matrix has the following form:

$$M_\nu = a \begin{pmatrix} v_{l_e}v_{l_e} & v_{l_e}v_{l_\mu} & v_{l_e}v_{l_\tau} \\ v_{l_\mu}v_{l_e} & v_{l_\mu}v_{l_\mu} & v_{l_\mu}v_{l_\tau} \\ v_{l_\tau}v_{l_e} & v_{l_\tau}v_{l_\mu} & v_{l_\tau}v_{l_\tau} \end{pmatrix} + x v_u v_u \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where $x = (\lambda_\nu^2 \langle T\rangle)/M_T$. This matrix is of rank 2. It has the same form as that given in Ref. [**?**] where a singlet field was introduced. With such a neutrino mass matrix, we will give a detailed analysis of neutrino oscillations, particularly for θ_{13} and CP violation. In addition to generating neutrino masses, triplet fields will play a key role in reconciling high-scale SUSY scenarios with the experimental result for the Higgs mass.

IV. NEUTRINO MIXING AND CP VIOLATION

Now we give a detailed analysis of the phenomenological consequences for neutrino physics. Experimental neutrino oscillation parameters are measured as follows [**?**, **?**]:

$\Delta m_{21}^2 = (7.59 \pm 0.20) \times 10^{-5}$ eV^2 and $\sin^2(2\theta_{12}) = 0.861^{+0.026}_{-0.022}$, $\Delta m_{32}^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) > 0.92$, $\sin^2(2\theta_{13}) = 0.088^{+0.049}_{-0.039}$.

Looking at the neutrino mass matrix M_ν, we will consider the case where $x v_u v_u \gg v_{l_\tau}^2$. Because M_ν has only two nonvanishing eigenvalues and has two origins, such a case is reasonable. While v_{l_τ}, which is Z_3-invariant, could be larger than $v_{l_{e(\mu)}}$, in general the largeness is a factor of 3 which is not considered in the analysis. This differs from the case of Ref. [**?**] where a somewhat unnatural cancellation between $x v_u v_u$ and $v_{l_\tau}^2$ was required. As a result, a normal hierarchical neutrino mass pattern is obtained:

$m_1 = 0$, $m_2 \approx \sqrt{a^2 v_{l_e} v_{l_e} + a^2 v_{l_\mu} v_{l_\mu}}$, $m_3 \approx \sqrt{a^2 x v_u v_u}$.

The matrix that diagonalizes M_ν has a simple form:

$$U_\nu \approx \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/\sqrt{1+r^2} & r/\sqrt{1+r^2} & s/\sqrt{1+r^2} \\ r/\sqrt{1+r^2} & -r/\sqrt{1+r^2} & s/\sqrt{1+r^2} \end{pmatrix},$$

where $r = v_{l_\mu}/v_{l_e}$ and $s = v_{l_\tau}/\sqrt{xv_u v_u}$. Taking $v_u \sim 200$ GeV and $M_{\tilde{m}} \sim 10^{12}$ GeV, and $x \sim 0.04$, the experimental results of neutrino mass squared differences can be recovered.

In the charged lepton mass matrix Eq. (3), we take $v_d \sim v_{l_{e(\mu,\tau)}}$, $y_\tau \sim 0.1$ and $\lambda_\mu \sim 10^{-2}$. The eigenvalues are:

$m_\tau \approx y_\tau v_d$, $m_\mu \approx \lambda_\mu v_{l_e}\sqrt{1+r^2}$, $m_e = 0$.

The matrix $U_l^\dagger$ which diagonalizes the mass squared matrix $M_l M_l^\dagger$ has the following form:

$$U_l \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ 1/\sqrt{1+r^2} & r/\sqrt{1+r^2} & \cdot \end{pmatrix},$$

where we have just listed the matrix elements relevant for our purpose.

Thus, the lepton mixing matrix $U_{PMNS} = U_l^\dagger U_\nu$ is obtained. It is parameterized in the following standard form:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \begin{pmatrix} s_{23}c_{13} & c_{23}c_{13} & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1),$$

where δ is the Dirac CP violation phase, and α and β are Majorana CP violation phases. In the case of $m_1 = 0$, the phase α is unphysical. Consequently,

$\tan\theta_{12} = 1/r$, $\sin\theta_{13} = s/\sqrt{1+r^2}$.

With the experimental result of $\tan\theta_{12}$, r is determined to be 0.53. In this case, $\sin\theta_{13} \approx 0.13$, which is very close to the value of 0.15 ± 0.02 given by the Daya Bay experiment [?].

Finally, θ_{23} can be obtained through the following equation:

$\tan\theta_{23} = \sqrt{1+r^2}\lambda_\tau v_{l_e}/(y_\tau v_d)$.

A large θ_{23} is quite natural, but there is no reason in this model to have θ_{23} being exactly 45°. Nevertheless, even global fitting allows θ_{23} to be as low as 42° at the 1σ level.

Now, let us consider CP violation in the lepton sector. Looking at mass matrices (3) and (11), because of the family symmetry they are very special: all matrix elements of the Dirac part can be made real by redefining relevant fields. This can be seen in the following way. Generally, sneutrino VEVs are complex because they are determined by the scalar potential in which soft masses are involved. In the charged lepton mass matrix, all phases can be absorbed into fields of left-handed and right-handed charged leptons. In the neutrino mass matrix, if we first do not consider the x term, it is easy to see that the phases can be rotated out—namely, after factorizing the Majorana phases out, the remaining part of the neutrino mass matrix is real. Then once the x term is added, we note that we always have the freedom to adjust its phase to be the same as that of $v_{l_\tau} v_{l_\tau}$ through a phase rotation of H_u (and H_d) field(s). Hence the Dirac part of the neutrino mixing matrix is real, and CP violation in neutrino oscillations vanishes in the symmetry limit.

Things become complicated when the nonvanishing electron mass is included. The electron mass is due to the following terms added to the mass matrix (3) [**?**, **?**]:

$\delta M_l \sim (y_\tau \tilde{m}_S v_d)/M_{\tilde{m}}$,

where $\tilde{m}_S$ are Yukawa soft masses where CP violating phases are expected to appear. δM_l itself is a general 3×3 matrix, and it is a perturbation to the mass matrix (3). Thus the Dirac CP violation phase in the lepton sector is found to be of order m_e/m_τ. For CP violation to be measured in neutrino oscillations, the Jarlskog invariant $J \sim (m_e/m_\tau) \sin\theta_{13} \sin\theta_{23} \sin\theta_{12} \sim 10^{-5}$–$10^{-3}$, where J stands for the Jarlskog invariant [**?**]. This is too small to be observed in current neutrino experiments.

Finally, the effective Majorana neutrino mass $m_{ee} = |\sum_i U_{ei}^2 m_i|$, which is to be measured in neutrinoless double β decays, is (10^{-3}) eV. Its exact value still depends on a Majorana phase which does appear as we have seen from the above-described procedure of phase rotation [**?**]. It should be mentioned that the discussion of CP violation is independent of numerical assumptions adopted in the neutrino mixing analysis.

It is remarkable to compare the mixing matrix of the lepton sector with that of the quark sector, which has been analyzed in detail in Ref. [**?**]. For the case of quarks, a Z_3 symmetry among the three-generation quark doublets is still present. It is also the soft Yukawa trilinear interactions that lead to CP violation. However, the mass story is a bit different. The roles of sneutrino VEVs and loop effects are switched: sneutrino VEVs give mass to the first generation, whereas loop effects contribute masses to charm and strange quarks. Loop effects appear in both up- and down-type quark masses. Therefore, it is expected that lepton mixing and quark mixing are qualitatively different. The final expression of the CKM matrix is obtained in Eq. (35) of Ref. [**?**], in which we can see that small V_{ub} and V_{cb}, and a large Cabibbo angle are natural. Furthermore, a large CP violation phase can also naturally appear.

V. HIGGS MASS

The real aim of introducing triplet fields T and $\bar{T}$ is for the Higgs mass. In the high-scale SUSY scenario, the Higgs quartic coupling evolves from a very high SUSY breaking scale $(g^2 + g'^2)\cos^2 2\beta$ [?] down to the EW scale (say 10^{12} GeV) with the usual boundary condition in the same way as in the SM. In the case of large $\tan\beta$, a Higgs mass of 141 GeV was predicted [?]. Because of sneutrino VEVs, the value will have a 1% decrease. Such a mass has been ruled out by recent results from ATLAS and CMS, which show that the Higgs mass is about 126 GeV [?]. To reduce the Higgs mass from 140 GeV to about 126 GeV, we make use of an observation by Giudice and Strumia that triplet fields can change the boundary condition of the Higgs quartic coupling by a considerable amount in the case of large $\tan\beta$ [?].

In Eq. (6), after integrating out the triplet fields, we get a new contribution to the boundary condition of the Higgs quartic coupling. The interaction $\lambda_\nu H_u H_u \bar{T}$ plays the main role, because its correction to the Higgs quartic coupling is proportional to $\sin^4\beta$, which is significant in the large $\tan\beta$ case:

$$\Delta\lambda \approx \frac{\lambda_\nu^4 \sin^4\beta}{16\pi^2}\left[\frac{m_T^2 + m_{\bar{T}}^2 + 2A_B M_T}{m_T^2 m_{\bar{T}}^2 - (B_T M_T)^2} + \frac{A_{\lambda_\nu}^2}{m_T^2}\right],$$

where $m_T^2 = m_{\bar{T}}^2 + M_T^2$ and $m_\beta^2 = m_{\bar{T}}^2 + M_T^2$. With the assumption that M_T^2 is much larger than m_{soft}^2, the above equation becomes:

$$\Delta\lambda \approx \frac{\lambda_\nu^4 \sin^4\beta}{16\pi^2}\left[\frac{(B_T - A_{\lambda_\nu})^2}{M_T^2}\right].$$

Obviously, this contribution is comparable to $(g^2 + g'^2)\cos^2 2\beta$. We note that this is consistent with our numerical choice for x in the last section, if $\lambda_\nu \sim 0.04$. Moreover, $\Delta\lambda$ can become negative in some parameter space so that it cancels $(g^2 + g'^2)\cos^2 2\beta$ and even makes the boundary condition negative. With an appropriate negative quartic coupling (about -0.02 as shown in [?]) at the high scale, a Higgs mass of about 126 GeV compatible with recent experimental results can be obtained.

A negative Higgs quartic coupling constant at 10^{12} GeV implies the instability of the SM vacuum. Note that at even higher energies, SUSY restores and the Higgs quartic coupling then becomes positive. Therefore, the true vacuum is at about 10^{12} GeV. This negative value of the coupling at the high scale remains in the safe region where the lifetime of the SM vacuum due to quantum tunneling is longer than the age of the Universe [?, ?].

VI. SUMMARY

In conclusion, we have discussed neutrino phenomenology in the framework that uses SUSY to account for the fermion mass hierarchy problem. One natural result of this model is that $\sin\theta_{13} \approx \sqrt{\Delta m_{sol}^2/\Delta m_{atm}^2} \approx 0.13$, consistent with experiments. Furthermore, it predicts that the CP violation effect in neutrino oscillations is vanishingly small. Additionally, the neutrino masses possess normal hierarchy, and θ_{23} is not necessarily 45°. These predictions can be checked in future experiments.

The SUSY breaking scale must be high in order to naturally obtain small neutrino masses. To reduce the high-scale SUSY-predicted Higgs mass, we have introduced $SU(2)_L$ triplet fields. They make the Higgs quartic coupling negative at the high scale. Our universe with the EW scale $\sim 10^2$ GeV is a false vacuum whose lifetime is longer than the age of the universe. The true vacuum is at about 10^{12} GeV. Because the vacuum energy in our current universe is tiny and positive, it is natural to guess that the true vacuum has a large negative cosmological constant.

A special form of the neutrino mass matrix Eq. (11) has been adopted in our analysis. While this is a reasonable assumption in the case of triplet fields, it can be made more accurate by introducing both singlets and triplets, where the singlets will be only for neutrino masses, and the role of triplets will be purely for Higgs mass reduction. This can be achieved by raising the triplet mass M_T and the corresponding soft mass m_T $(\bar{T})$ by two orders of magnitude while keeping their ratio unchanged.

In fact, in this model, the scale of 10^{12} GeV or so is more fundamental. The effective theory below this scale is just the SM, and the EW scale is a kind of accidental result via fine-tuning. Conventional WIMP dark matter therefore does not exist. However, we note that this high scale is close to that of the axion. The axion might be the dark matter in this model. Cosmological aspects of this model are under study.

In the near future, if experiments show that the SM is the full theory at the TeV scale, then leptonic CP violation δ will be almost the last parameter to be fixed for elementary particle physics. It would also be almost the last nontrivial physical quantity to verify various flavor models. Since the whole flavor puzzle is the most complicated problem of the SM, SUSY as well as its breaking just provides a simple yet complicated enough framework to understand the puzzle. SUSY should have a use because of its beauty and power.

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Note: Figure translations are in progress. See original paper for figures.