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Electroweak symmetry breaking from supersymmetry breaking with a bosonic seesaw mechanism

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We introduce the idea of *bosonic seesaw mechanism* in analogy with the seesaw mechanism. Bosonic seesaw is a new symmetry breaking mechanism, and we apply it to explain electroweak symmetry breaking as an inevitable consequence of supersymmetry breaking. The breaking of electroweak symmetry occurs at tree level once supersymmetry is broken. Absence of color/charge breaking in this model is related to doublet-triplet splitting in the grand unified theory. An extension of the minimal supersymmetric standard model with a weak triplet shows very interesting results, especially when $\mu = 0$. It provides natural understanding of why we have only electroweak symmetry breaking rather than having color/charge breaking. In the limit $\mu = 0$, the model predicts very light chargino mass, 104 GeV, while Higgs is heavy, 130 GeV.

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The standard model (SM) has a beautiful structure of explaining all the matters and forces except gravity in terms of quark/lepton(s) and gauge interactions. All the quarks and leptons are massless as long as electroweak symmetry is unbroken, and they can get mass from Yukawa interactions only after electroweak symmetry breaking. Within the framework of the standard model, Higgs potential can be arbitrary and we choose the sign of the coefficient of the quadratic (quartic) term to be negative (positive) such that the Higgs potential has a desired Mexican hat shape. It would not be easy to understand why the quadratic term has a negative sign while the quartic term is positive within the standard model.

The SM is just regarded as a low energy effective theory of some extended one and the gauge hierarchy problem suggests a modification of the standard model at TeV scale. Supersymmetry (SUSY) [1,2] is one of the most promising candidates for it. In supersymmetric extensions of the standard model, we can get a better understanding of the electroweak symmetry breaking. First of all, the Higgs potential is no longer arbitrary and should be a sum of supersymmetric F/D terms and soft supersymmetry breaking terms. The quartic term is calculated from gauge couplings and is positive definite. The quadratic term (soft terms) is a sum of the supersymmetric mass term (μ term) and soft supersymmetry breaking terms which are calculable in a certain mediation mechanism of supersymmetry breaking. In the minimal supersymmetric standard model (MSSM) with gauge mediated SUSY breaking [3–5], a radiative correction by large top Yukawa coupling gives negative Higgs mass squared. If μ were zero, the above picture might have been beautiful and could be considered as a possible explanation of the electroweak symmetry breaking. However, in reality, the electroweak symmetry breaking is a surprising cancellation of $\mu^2 \sim (500\ \text{GeV})^2$ and the Higgs soft scalar mass squared $m_{H_u}^2$ [6]. If μ were slightly larger, we would never have the electroweak symmetry breaking. And if μ were slightly smaller, the Higgs would develop its vacuum expectation value (VEV) exponentially larger than the weak scale [7]. Thus, it is desirable to consider models in which the weak scale electroweak symmetry breaking can be explained for a broad range of parameters.

In this paper, we first introduce a simple idea called the "bosonic seesaw mechanism." We apply the bosonic seesaw mechanism to explain the electroweak symmetry breaking. When a down-type Higgs couples to the extra vectorlike pair of Higgs, we can soften the little hierarchy problem. Finally, we consider a model in which the electroweak symmetry is closely tied up to the supersymmetry.

Let us briefly discuss the conventional seesaw mechanism explaining the lightness of neutrino masses [8,9]. For ν, the left-handed neutrino, which is an $SU(2)_L$ doublet, and N a singlet, the possible interactions are

$$\mathcal{L}_\nu = -MNN + \lambda_\nu HLN + \text{H.c.}, \tag{1}$$

where $H = (H^+, H^0)$ is the Higgs doublet and $L = (\nu, l^-)$. After the electroweak symmetry breaking, it becomes

$$M_\nu \begin{pmatrix} \nu \\ N \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}, \tag{2}$$

where $m_D = \lambda_\nu \langle H^0 \rangle$. The lightest neutrino mass for $m_D \ll M$ is then

$$m_\nu = -\frac{m_D^2}{M}. \tag{3}$$

Note the sign of the lighter eigenvalue. As the determinant of the matrix is negative definite ($-m_D^2$) and the heavier one is nearly M, the lighter eigenvalue is negative definite. The result is valid as long as $m_D \ll M$. We can make the mass term to be positive definite by the field redefinition of neutrinos. Therefore, this observation is not important for

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neutrinos (fermions), but it will turn out to be very important for later consideration.

The bosonic seesaw mechanism works for bosons instead of fermions (neutrinos). Although the mechanism works for any scalar fields (superfields), here we take Higgs as an example for a clear illustration. Supersymmetric extension of the standard model requires two Higgs chiral superfields H_u and H_d. Suppose there is an additional massive pair H'_u and H'_d, the electroweak doublets with the opposite hypercharge. Let $X = \cdots + F_X\theta^2$ be a superfield representing supersymmetry breaking $F = \langle F_X \rangle \neq 0$. For the superpotential

$$W = \lambda_1 X H'_u H_d + M H'_u H'_d, \quad (4)$$

the scalar mass squared matrix for H_d, H'^*_u is

$$\hat{\mathcal{M}}^2 = \begin{pmatrix} 0 & \lambda_1^* F^* \\ \lambda_1 F & |M|^2 \end{pmatrix}. \quad (5)$$

When $\sqrt{F} \ll M$, the lightest scalar mass squared becomes negative definite,

$$m^2_{H_d} = -\left|\frac{\lambda_1 F}{M}\right|^2.$$

Whenever $F \neq 0$, the mass squared is negative and we end up with symmetry breaking. Therefore, at tree level, we obtain the electroweak symmetry breaking as a consequence of supersymmetry breaking. We can do the same thing to H_u instead of H_d. Note that the sign here is physical as the matrix is for scalar mass squared. It is called bosonic seesaw mechanism as it is opposed to the usual seesaw mechanism, which works for the fermions.

The bosonic seesaw mechanism shows a similarity to the (fermionic) seesaw mechanism.

(i) There are heavy states (heavy Higgs vs N).
(ii) There are interactions between heavy and massless states (H'_u and H_d vs ν and N).
(iii) Off-diagonal elements are generated if fields get VEVs ($X \to \langle F_X \rangle \neq 0$ vs $H \to \langle H^0 \rangle \neq 0$).

The crucial difference is the negative sign of the bosonic seesaw mechanism, which cannot be eliminated by rephasing scalar fields. In general, $\langle X \rangle \neq 0$ and we can redefine fields and couplings such that $\tilde{X} = X - \langle X \rangle$ does not have a scalar VEV ($\langle \tilde{X} \rangle = 0$). At the same time, we can redefine

$$\tilde{H}_d = H_d \cos\alpha - H'_d \sin\alpha, \quad (6)$$

$$\tilde{H}'_d = H_d \sin\alpha + H'_d \cos\alpha \quad (7)$$

with $\tan\alpha = \lambda_1 \langle X \rangle / M$. Then we obtain a more general superpotential,

$$W = \lambda_1 \cos\alpha \tilde{X} H'_u \tilde{H}_d + \lambda_2 \sin\alpha \tilde{X} H'_u \tilde{H}'_d + M \sec\alpha H'_u \tilde{H}'_d. \quad (8)$$

In order to make the expression simple, we will use $\lambda_1 \cos\alpha \to \lambda_1$, $\lambda_2 \sin\alpha \to \lambda_2$, $M \sec\alpha \to M$, $\tilde{X} \to X$, $\tilde{H}_d \to H_d$, and $\tilde{H}'_d \to H'_d$.

$$W = \lambda_1 X H'_u H_d + \lambda_2 X H'_u H'_d + M H'_u H'_d. \quad (9)$$

The only difference compared to $\langle X \rangle = 0$ is the appearance of a new term $\lambda_2 X H'_u H'_d$, which is allowed by symmetry anyway. Now Yukawa couplings are accordingly

$$W = \lambda_u H_u Q u^c + \lambda_d H_d Q d^c + \lambda'_u H'_u Q u^c. \quad (10)$$

Notice the new appearance of the last term.

From now on, we focus on the application of the bosonic seesaw mechanism to the electroweak symmetry breaking. As we have two Higgs fields H_u and H_d in MSSM, there are three possibilities. First, H_u couples to heavy Higgs. Second, H_d couples to it. Finally, both of them couple to it. When there is no radiative correction, the first option looks the most natural. However, we know that usual renormalization group (RG) running gives large negative radiative corrections driven by large top Yukawa couplings (stop contribution) which is already too negative. Hence, to add the bosonic seesaw contribution would make the situation worse. This rules out the first and the third option. The second option remains as the best. In addition to this, if both of them couple to heavy Higgs and X, we cannot make them light, and the third option does not work. Before having SUSY breaking, either the first or the second option has one massless Higgs pair which does not mix with the massive Higgs pair. This is no longer true if we couple the heavy Higgs to both H_u and H_d. The possible way out is to introduce two pairs of massive Higgs such that each pair couples only to one Higgs (either H_u or H_d). Here we consider only the second possibility in this paper.

As H'_u and H'_d couple to X directly, they are the messengers of SUSY breaking and M is the messenger scale. We can calculate soft terms mediated by gauge interactions. We also assume that there is a pair of color triplet Higgs fields which complete the messenger fields into $SU(5)$ multiplets. The soft terms from gauge mediation are positive definite [10].

$$m^2_\Phi = \sum_i 2 c_i \left(\frac{\alpha_i}{4\pi}\right)^2 \Lambda^2, \quad (11)$$

where $\Lambda = |\lambda_2 F/M|$ and c_i is the quadratic Casimir of the ith gauge group. Note that $\lambda_1 \sim 10^{-2}\lambda_2$ is required to have $\Lambda \sim 10$ TeV while $m^2_{H_d} \sim 100$ GeV. Until now the only difference with the usual MSSM is the tree-level contribution from the bosonic seesaw, which is negative definite.

The most interesting consequence comes with the addition of the electroweak triplet Σ. Let us explain why we need Σ and how it brings an interesting result.

In MSSM, the nice mechanism of radiative electroweak symmetry breaking is spoiled by a large μ term. The large μ term in MSSM is due to the fact that we have not seen Higgs yet. In MSSM, the quartic couplings are given by gauge couplings and the Higgs mass is predicted to be light. $m^2_H > 114$ GeV requires a large radiative correction and it is possible only with heavy stop. If stop is heavy, radiative corrections are too large, and the electroweak symmetry breaking becomes large unless a large μ term cancels it. The lightness of Higgs mass in MSSM is mainly due to the small quartic terms from gauge interactions, and it can be relaxed if there are additional quartic couplings in the theory in addition to the usual D term. Thus, we consider the modification of MSSM to give the additional quartic terms.

The most transparent application of the bosonic seesaw mechanism comes out if $\mu = 0$. However, the limit $\mu = 0$ in MSSM poses several problems [11].

(i) Peccei-Quinn (PQ) symmetry and R symmetry: As the Higgs fields carry PQ and R charge and the symmetry is exact in the limit $\mu = 0$, once they get VEVs, there appears a massless Goldstone boson which is in conflict with experiments.

(ii) Electroweak symmetry breaking: If H_u gets a VEV from negative $m^2_{H_u}$, H_d gets its VEV through the $B\mu$ term. Therefore, if $\mu = 0$ ($B\mu = 0$), the down-type quarks and charged leptons cannot get their masses.

(iii) Chargino mass: If $\mu = 0$, Higgsinos can get their mass only by the electroweak symmetry breaking, and the lightest chargino mass is always lighter than M_W, which cannot be compatible with the current bound on the lightest chargino mass, 104 GeV.

These problems can be solved if extra fields are introduced. In the next to minimal supersymmetric standard model (NMSSM), an extra singlet replaces the μ term. The singlet gets a VEV and it generates a μ term effectively. Then the electroweak symmetry breaking is a fine-tuning just as in MSSM [12]. An alternative way is to introduce an extra weak triplet Σ with no hypercharge.

Let us consider the most interesting limit $\mu = 0$ (μ-less SSM). We can forbid the μ term by a discrete symmetry, so-called "U parity," which is a Z_2 subgroup of Peccei-Quinn symmetry. Under the U parity,

$$(H_u, u^c, \Sigma) \rightarrow -(H_u, u^c, \Sigma).$$

The most general superpotential consistent with the U parity is [13]

$$W = \frac{M_\Sigma}{2}\,\mathrm{tr}\Sigma^2 + \lambda_{\Sigma_1} H_u \Sigma H_d + \lambda_{\Sigma_2} H_u \Sigma H_d'. \qquad (12)$$

These terms are enough to break PQ and R symmetry. At the same time, chargino mass can be heavier than M_Z as we have new sources for it.

Soft supersymmetry breaking terms are

$$V_{\mathrm{soft}} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_\Sigma\,\mathrm{tr}\Sigma^\dagger\Sigma + A\lambda_{\Sigma_1} H_u \Sigma H_d + BM_\Sigma\,\mathrm{tr}\Sigma^2 + \mathrm{H.c.} \qquad (13)$$

The neutral component of Σ gets a VEV once H_u and H_d get VEVs [13],

$$v_\Sigma = \frac{\lambda_{\Sigma_1}\frac{M_\Sigma}{2}v^2}{m^2_\Sigma + M^2_\Sigma + B_\Sigma M_\Sigma + \frac{1}{2}\lambda_{\Sigma_1}{}^2 v^2}. \qquad (14)$$

$v_\Sigma < 9$ GeV is obtained if m_Σ is about TeV. For instance, with $\lambda_{\Sigma_1} = 1$, $M_\Sigma = 150$ GeV, and $m_\Sigma = 1$ TeV (even with $B_\Sigma = 0$), we get $v_\Sigma = 4.3$ GeV.

Let us go back to the calculation of soft terms. As our messenger fields have direct couplings with matter/Higgs fields, there are additional contributions. The Yukawa mediated ones are calculated using the formalism of analytic continuation into superspace [14–16],

$$\Delta m^2_{H_u} = \left[\frac{3\alpha^2_{\Sigma_2}}{4\pi^2} + \frac{\alpha_{\Sigma_2}\alpha_{\lambda_2}}{4\pi^2}\right]\Lambda^2,$$

$$\Delta m^2_{H_d} = \left[-\frac{\alpha_{\Sigma_1}\alpha_{\Sigma_2}}{2\pi^2}\right]\Lambda^2, \qquad \Delta m^2_{Q,u^c} = \left[-\frac{\alpha_t\alpha_{\Sigma_2}}{8\pi^2}\right]\Lambda^2,$$

$$\Delta m^2_\Sigma = \left[\frac{3\alpha_t\alpha_{\Sigma_2}}{4\pi^2} + \frac{3\alpha^2_{\Sigma_2}}{4\pi^2} + \frac{\alpha_{\Sigma_2}\alpha_{\lambda_2}}{4\pi^2} - \frac{5\alpha\alpha_{\Sigma_2}}{4\pi^2}\right]\Lambda^2,$$

where $\alpha = g^2/4\pi$ is the $SU(2)$ gauge coupling and $\alpha_f = f^2/4\pi$ are similarly defined Yukawa couplings for $f = \lambda_1, \lambda_2, \lambda_{\Sigma_1}, \lambda_{\Sigma_2}, \lambda_t$. We assume $\lambda_t' \ll 1$ and neglect its contribution. Other Yukawa couplings are also neglected as they are small. The effects are summarized as follows.

(i) H_d:

$$m^2_{H_d} = -|\lambda_1|^2\Lambda^2 + \frac{3\alpha^2_2}{32\pi^2}\Lambda^2 - \frac{\alpha_{\Sigma_1}\alpha_{\Sigma_2}}{2\pi^2}\Lambda^2. \qquad (15)$$

Here the $U(1)_Y$ contribution is omitted. Soft scalar mass squared is negative at the tree level from the bosonic seesaw mechanism. There are threshold corrections from gauge and Yukawa interactions and the sign is opposite. If Yukawa and gauge couplings are of similar size, the threshold corrections at the messenger scale cancel with each other. Therefore, negative mass squared at the tree level dominates.

(ii) H_u: Threshold corrections at the messenger scale are positive for both gauge and Yukawa contributions. We have slightly larger $m^2_{H_u}$ compared to the MSSM with gauge mediation. We should also consider negative one-loop correction from messenger scale to the weak scale $-(3/4\pi^2)m^2_{\tilde{t}}\log(M/m_{\tilde{t}})$.

(iii) Σ: Threshold corrections are positive for gauge and Yukawa contributions. Thus, we get m^2_Σ heavier than other soft scalar masses, which is necessary to suppress the VEV of Σ compared to H_u and H_d.

(iv) Third generation Q, u^c ($\rightarrow$ stop): Threshold correction from Yukawa mediation is negative. We get lighter stop mass compared to the MSSM, which makes the negative contribution to $m^2_{H_u}$ smaller than usual.

The most challenging phenomenological constraint comes from chargino mass bound combined to the precision data.

The chargino mass is obtained from Yukawa interactions (A: Higgsino–W-ino–Higgs and B: Higgsino-ψ_Σ-Higgs) in the μ-less theory [17]. A is the gauge coupling and B is a new Yukawa coupling λ_{Σ_1} that violates custodial $SU(2)$ symmetry. The bound on the precision variable T ($T < 0.6$) restricts λ_{Σ_1} ($\lambda_{\Sigma_1} < 0.6$) [17]. For $\lambda_{\Sigma_1} \sim 1$, we obtain the lightest chargino mass to be 104 GeV, which is the bound from LEP II. The chargino masses are (104, 119, 252) GeV for $\lambda_{\Sigma_1} = 1$, $(M_2, M_\Sigma) = (120, 150)$ GeV. Note that if we allow nonzero μ, we can satisfy the chargino mass bound with a smaller λ_{Σ_1}. More precise calculation of T is needed as we deal with the light spectrum (charginos are near 100 GeV). For the neutralinos, the lower mass bound 40 GeV is easily satisfied.

The Higgs mass can be calculated if all the parameters are chosen. As we have new quartic couplings for the Higgs from $W = \lambda_1 H_u \Sigma H_d$, the lightest scalar Higgs mass is heavier than the one in the MSSM and is around 120 to 130 GeV before considering the one-loop correction. Therefore, in this model we do not need to tune the parameters to raise up the Higgs mass beyond the current bound 114 GeV. The bosonic seesaw mechanism gives $m_{H_d}^2 < 0$ at the messenger scale and $m_{H_u}^2$ is driven to be negative by RG running to the weak scale. Both $m_{H_u}^2$ and $m_{H_d}^2$ are negative at the weak scale, and the minimum is at around $\tan\beta = v_u/v_d \sim \mathcal{O}(1)$. Unlike in the MSSM, the potential is not unbounded from below for $m_{H_u}^2 < 0$, $m_{H_d}^2 < 0$, as the new quartic coupling λ_1 prevents them from running away along the D-flat direction.

In this paper, we proposed a new mechanism to understand the electroweak symmetry breaking. As H_d couples directly to the messenger of supersymmetry breaking, the soft scalar mass squared is negative by the bosonic seesaw mechanism when supersymmetry is broken. The soft scalar mass squared of H_u is driven to be negative and the symmetry breaking minimum is at around $\tan\beta = v_u/v_d \sim \mathcal{O}(1)$. There is a new $SU(2)_L$ triplet Σ which couples to H_u and H_d. The lightest chargino mass is predicted to be light due to the absence of supersymmetric mass μ and lies just above the current mass bound 104 GeV. The lightest Higgs mass is heavy, as we have a new quartic coupling. All the soft parameters appear from gauge mediation and new Yukawa (Higgs) mediation and they are calculable. Gauge mediation gives positive definite soft scalar masses, which guarantees the absence of color/charge breaking minima. Yukawa (Higgs) mediation gives negative contributions to H_d and the third generation Q and u^c (stop) and positive contributions to H_u and Σ. The contributions of Yukawa (Higgs) mediation softens the little hierarchy problem of MSSM. As Higgs can be heavy, the fine-tuning problem is no longer severe.

The setup considered here naturally arise from the five-dimensional geometric setup [18]. The orbifold grand unified theory (GUT) fixes the location of gauge and Higgs fields to be in the bulk, and the distant brane is a source of supersymmetry breaking. In this case, Higgs is very special and can feel the supersymmetry breaking directly. The massive vectorlike fields introduced here are just the massive Kalaza-Klein towers of bulk Higgs fields. Gaugino mediation can be considered at the same time, as there is no symmetry preventing the couplings of supersymmetry breaking fields with gauge sector. In the orbifold GUT, the doublet-triplet splitting of Higgs fields is explained by the boundary condition (or orbifold projection), and the setup given in this paper naturally arises from higher dimensions. More precisely, only H_d should be bulk fields as in Ref. [19]. The setup has been studied to understand the top/bottom mass hierarchy without large $\tan\beta$ in Ref. [19]. Furthermore, the smallness of λ_1 compared to λ_2 can be explained by the zero mode localization of H_d [20–22].

We proposed a new idea called the bosonic seesaw mechanism. Once supersymmetry is broken, at the same time it gives the VEV to the Higgs fields; i.e., quarks and leptons get their masses. The mechanism works nicely even if $\mu = 0$, though we need an additional weak triplet. The chargino remains light (near 104 GeV) when $\mu = 0$, and it is robust against radiative corrections. Higgs is heavy (about 130 GeV before considering radiative corrections), but the full spectrum of Higgs can be obtained only after considering the radiative corrections, and we leave the detailed calculation of it for future work. The bosonic seesaw mechanism can be applied in a different way in other problems.

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unbounded from below and Higgs gets a VEV far larger than the weak scale soft scalar masses or a Planck scale VEV. It is because there is a D-flat direction along which there is no quartic coupling, and the potential is bounded from below once the quadratic term is negative. μ slightly smaller means when the condition is violated.

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