SUSY Extended Higgs Sector and SUSY Strong Dynamics

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We consider an extended Higgs sector that arises as a low-energy description of a strongly-coupled SUSY gauge theory. This model predicts the presence of extra superfields that couple with the Higgs superfields through large coupling constants. Large radiative corrections involving the extra fields can realize strongly first order electroweak phase transition, which is a vital requirement for electroweak baryogenesis scenario. At the same time, the large radiative corrections lead to significant deviations in the Higgs boson triple coupling and Higgs-to-diphoton branching ratio, which are testable at the ILC.

I. INTRODUCTION

Although the Higgs-like boson has been discovered, we have not yet revealed the structure of the Higgs potential. In building models of the Higgs sector, we adopt electroweak baryogenesis scenario as a guiding principle. It is known that successful electroweak baryogenesis relies on sufficient amount of CP violation and strongly first order electroweak phase transition (EWPT), both of which are not realized in the standard model (SM) with 126 GeV Higgs boson mass. The latter condition on EWPT is directly connected to the structure of the Higgs potential and may give a clue to the study on the Higgs sector. We therefore discuss extensions of the SM Higgs sector that enable strongly first order EWPT. In general, models that realize strongly first order EWPT through enhanced thermal cubic term necessarily contain large coupling constants in the Higgs sector, which blow up at a Landau pole below the Planck scale. Extended Higgs models with large coupling constants in the Higgs sector have been investigated in refs. In such cases, the models must be replaced by more fundamental theories above the Landau pole.

We propose an ultraviolet (UV) complete model of an extended Higgs sector that incorporates such large coupling constants. Our model is based on supersymmetric (SUSY) SU(2) gauge theory with six doublets, similar to the minimal fat Higgs model. This gauge theory becomes strongly-coupled at an infrared (IR) scale, which we call ‘confinement scale’, and below that scale, the theory is described in terms of mesonic superfields with an emergent effective superpotential which contains large coupling constants. We identify the mesonic superfields with the Higgs superfields of the SUSY SM as well as extra iso-spin doublet and singlet chiral superfields in an extended Higgs sector, and identify the effective superpotential with that of the extended Higgs sector. In this way, we introduce, with a solid UV completion, extra superfields that couple with the Higgs superfields through large coupling constants. A feature of the model is that the scale at which the large coupling constants blow up is identified with the confinement scale of the SUSY gauge theory.

We investigate the phenomenology of the SUSY extended Higgs sector that has been obtained as the low-energy effective theory of the SUSY SU(2) gauge theory. With a benchmark mass spectrum, we calculate the strength of EWPT and look for parameter regions where strongly first order EWPT occurs. We further calculate the triple coupling constant of the SM-like Higgs boson and the decay branching ratio into di-photon, whose deviations from the SM values give collider signatures of the model.

II. MODEL

We consider a SUSY extended Higgs sector that emerges as a low-energy effective theory of a new SUSY SU(2)_{H} gauge theory with six doublet chiral superfields, which are also charged under SM gauge groups SU(2)_{L} \times U(1)_{Y}. A Z_{2} parity is assigned to the doublets to forbid large flavor changing neutral currents in the resultant extended Higgs sector. One can say that the SUSY SU(2)_{H} gauge theory is the UV picture of the model. The field content of the SUSY SU(2)_{H} gauge theory is summarized in Table 1.

The SU(2)_{H} gauge theory becomes strongly-coupled at an IR scale, which we call ‘confinement scale’ \Lambda_{H}, and below \Lambda_{H}, the low-energy effective theory is described in terms of mesonic chiral superfields. In our model, the mesonic superfields are identified with the Higgs doublets of the SUSY SM as well as extra chiral superfields in the extended Higgs sector. One can say that the extended Higgs sector is the IR picture of the model. The Higgs sector contains two SU(2)_{L} doublet, two charged singlet and five neutral singlet chiral superfields, in addition to the two Higgs doublets of the SUSY SM. The field content is summarized in Table 2.
The scalar components of the superfields $N, N_{\Phi}, N_{\Omega}$ gain vacuum expectation values, which give effective $\mu$-terms for the other superfields. The physical components of $N_{\Phi}, N_{\Omega}$ do not contribute to the one-loop effective potential for the SUSY SM Higgs scalars, and hence can be neglected in phenomenological studies. The superpotential of the phenomenologically relevant part of the Higgs sector is then given by

$$W_{\text{Higgs}} = -\mu H_u H_d - \mu_{\Phi} H_u \Phi_d - \mu_{\Omega} (\Omega^+ \Omega^- - \zeta \eta)$$

$$+ \hat{\lambda} \left\{ n H_u H_d + H_d H_u \zeta + H_u \Phi_d \eta - H_u \Phi_d \Omega^- - H_d \Phi_d \Omega^+ \right\}, \quad (1)$$

where $n$ denotes the physical component of $N$. $\hat{\lambda}$ denotes a running coupling constant for the superfields in the extended Higgs sector. Naïve Dimensional Analysis (NDA) [6] suggests that the coupling constant $\hat{\lambda}$ becomes non-perturbative at a similar scale where the SUSY SU(2)$_H$ gauge theory in the UV picture becomes strongly-coupled, i.e., the confinement scale $\Lambda_H$. Therefore, with a given renormalization group equation of $\hat{\lambda}$, the value of $\hat{\lambda}$ at the electroweak scale is in one-to-one correspondence with the confinement scale $\Lambda_H$.

The soft SUSY breaking terms are introduced as follows:

$$L_{\text{soft}} = -m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - m_{\Phi_u}^2 \Phi_u^\dagger \Phi_u - m_{\Phi_d}^2 \Phi_d^\dagger \Phi_d$$

$$- m_{\Omega}^2 \Omega^+ \Omega^- - m_{\zeta}^2 \zeta \zeta - m_{\eta}^2 \eta \eta - B_{\mu} H_u H_d - B_{\mu} H_d H_u - B_{\mu} (\Omega^+ \Omega^- - \zeta \eta)$$

$$- A_{\zeta} H_d \Phi_u \zeta - A_{\eta} H_u H_d \eta - A_{\Omega} H_u \Phi_d \Omega^- - A_{\Omega} H_d \Phi_d \Omega^+.$$

Similar to the minimal SUSY SM, electroweak symmetry breaking occurs with the help of soft SUSY breaking terms.

The Yukawa couplings, including the top quark Yukawa coupling, are introduced in the same way as in the minimal fat Higgs model [5].

## III. ELECTROWEAK PHASE TRANSITION IN THE MODEL

Using finite-temperature effective potential and the methods introduced in [7, 8], we make a numerical analysis on the order of EWPT, $v_C/T_C$, where $T_C$ and $v_C$ respectively denote the critical temperature and the value of

| Field | SU(2)$_L$ | U(1)$_Y$ | Z$_2$ |
|-------|-----------|-----------|-------|
| $T_1$ | 2         | 0         | +     |
| $T_2$ | 1         | +1/2      | +     |
| $T_3$ | 1         | −1/2      | +     |
| $T_4$ | 1         | +1/2      | −     |
| $T_5$ | 1         | −1/2      | −     |

**TABLE I:** SM charge and $Z_2$ parity assignments on the $SU(2)_H$ doublets, $T_i$.

| Field | SU(2)$_L$ | U(1)$_Y$ | Z$_2$ |
|-------|-----------|-----------|-------|
| $H_u$ | 2         | +1/2      | +     |
| $H_d$ | 2         | −1/2      | +     |
| $\Phi_u$ | 2     | +1/2      | −     |
| $\Phi_d$ | 2   | −1/2      | −     |
| $\Omega^+$ | 1   | +1        | −     |
| $\Omega^-$ | 1   | −1        | −     |
| $\zeta, \eta$ | 1 | 0         | −     |
| $N, N_{\Phi}, N_{\Omega}$ | 1 | 0         | +     |

**TABLE II:** The chiral superfields in the extended Higgs sector.
the order parameter at that temperature.

The benchmark mass spectrum is as follows. For the SUSY SM sector,

$$\tan \beta = 15 , \quad m_{H^\pm} = 350 \text{ GeV}, \quad \mu = 200 \text{ GeV}, \quad M^t = M^b = 2000 \text{ GeV},$$

(3)

where $M^t$ and $M^b$ respectively denote the soft SUSY breaking masses for the SUSY tops and bottoms. For the $Z_2$-odd sector,

$$\mu = 550 \text{ GeV}, \quad \bar{m}_{\Phi^d} = \bar{m}_{\Omega^+} = \bar{m}_{\Upsilon} = 1500 \text{ GeV}, \quad \bar{m}_\eta = 2000 \text{ GeV},$$

(4)

where $\bar{m}_s$ denotes the square root of the sum of the $\mu$-term squared and the soft SUSY breaking mass squared for the field $s$. The following two quantities are the free parameters in this analysis:

$$\lambda ( \equiv \hat{\lambda}(M_Z) ) , \quad m_0 ( \equiv \bar{m}_{\Phi^+} = \bar{m}_{\Omega^-} ) .$$

(5)

We tune the value of the stop mixing term to realize $m_h = 126 \text{ GeV}$.

In Figure 1, we show the contour plot for the coupling constant $\lambda ( \equiv \hat{\lambda}(M_Z) )$. The strength of EWPT, $v_C/T_C = 1$, is also displayed. We find that strongly first order phase transition, $v_C/T_C \gtrsim 1$, takes places with our benchmark mass spectrum for $\lambda \gtrsim 1.6$ when $m_{\Phi^0} \approx 60 \text{ GeV}$ (for $\lambda \gtrsim 1.8$ when $m_{\Phi^0} \approx 130 \text{ GeV}$). Note that, in our model, $\lambda \simeq 1.6$ corresponds to $\Lambda_{\text{UV}} \simeq 15 \text{ TeV}$ and $\lambda \simeq 1.8$ does to $\Lambda_{\text{UV}} \simeq 5 \text{ TeV}$.

**IV. COLLIDER SIGNATURES OF THE MODEL**

With the benchmark mass spectrum eqs. (3, 4, 5), we make a numerical analysis on the decay branching ratio of the Higgs boson into diphoton and the triple Higgs boson coupling, and study the correlation between these quantities and the strength of EWPT.

In Figure 2, we combine the contour plot for the ratio of the Higgs-to-diphoton branching ratio over its SM value, $\mu_{\gamma\gamma}$, with a line indicating the strength of EWPT, $v_C/T_C = 1$. We find that the Higgs-to-diphoton...
branching ratio decreases by more than 20\% with our benchmark mass spectrum when the strongly first order EWPT with \( v_C/T_C \gtrsim 1 \) is realized.

In Figure 3 we combine the contour plot for the deviation of the triple Higgs boson coupling from the SM value, \( \Delta \lambda_{hhh}/\lambda_{hhh}|_{SM} \) (black dashed lines), with a line indicating the strength of EWPT \( v_C/T_C = 1 \) (red solid line), on the plane of the mass of the lightest \( Z_2 \)-odd charged particle \( m_{\Phi'_{1\pm}} \) and the mass of the lightest \( Z_2 \)-odd neutral particle \( m_{\Phi'_{10}} \). The parameters are fixed according to eqs. (3) and (4). To summarize, we confirm that sufficiently strongly first order EWPT for successful EWBG can be realized.
with our benchmark mass spectrum. In order to have $\nu_C/T_C \gtrsim 1$, we need $\lambda > 1.6$ provided the lightest $Z_2$-odd neutral scalar is heavier than 50 GeV. This corresponds to the confinement scale $\Lambda_H$ lower than about 15 TeV. In the parameter regions where strongly first order EWPT occurs, the Higgs-to-diphoton branching ratio, $Br(h \to \gamma\gamma)$, and the triple Higgs boson coupling, $\lambda_{hhh}$, significantly deviate from the SM values. These are principally due to loop corrections involving light $Z_2$-odd scalars, which are also responsible for strongly first order EWPT. With the benchmark mass spectrum, $Br(h \to \gamma\gamma)$ decreases by about 20% and $\lambda_{hhh}$ increases by more than about 20%, both of which may be observed at the future International Linear Collider [9, 10].

V. CONCLUSIONS

We have discussed the correlation among the strength of EWPT, the Higgs-to-diphoton branching ratio and the triple Higgs boson coupling in the extended Higgs sector with large coupling constants and the 126 GeV Higgs boson, which emerges as a low-energy effective theory of the SUSY SU(2)$_L$ gauge theory with confinement. In our benchmark mass spectrum, the condition of quick sphaleron decoupling for EWBG, $\nu_C/T_C \gtrsim 1$, determines the scale of the Landau pole to be below about 15 TeV, which corresponds to the confinement scale of the SU(2)$_L$ gauge theory. We have found that the Higgs-to-diphoton branching ratio deviates negatively from the SM prediction by about 20% and the triple Higgs boson coupling deviates positively by more than about 20%. Such deviations can be observed at future collider experiments.

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