Higgs bosons of a supersymmetric $U(1)'$ model

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Seung Woo Ham (KAIST)
based on collaboration with Sun Kun Oh

1. Introduction

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1. Introduction

(a) Supersymmetry (Motivation)

◇ **No-Go theorem; Theory**

Poincare group (space-time maximal symmetry, Boost, Translation, Rotation) $\Rightarrow$ Super-Poincare group (Majorana Spinors; Super Charge: SUSY Invariant Quantity)

◇ **Superstring; SUSY was originally introduced into physics in the context of string theory, Ryder, Quantum Field Theory**

(b) Non-Minimal Supersymmetric Standard Models (Motivation)

◇ **μ-problem ($\sim \mu H_1 H_2$); J. E. Kim and H. P. Nilles, PLB138, 150 (1984)**

Higgs Singlet: Pierre Fayet, NPB90, 104 (1975)

- **μ-parameter: $\mu \sim \lambda\langle N\rangle$, VEV of Higgs singlet**

$\odot$ Non-Minimal Supersymmetric Standard Models (Non-MSSMs)

- Gauge Group

$\odot$ $SU(2) \times U(1)$; **Two Higgs doublets + One Higgs singlet** (N)

The Next-to-MSSM (NMSSM)

S_1, S_2, S_3, P_1, P_2, $H^\pm$, $\tilde{\chi}_1^0 - \tilde{\chi}_5^0$

$\odot$ $SU(2) \times U(1) \times U(1)'$; **Two Higgs doublets + One Higgs singlet** (S)

The $U(1)$-extended Supersymmetric Standard Model (USSM)

S_1, S_2, S_3, A, $H^\pm$, Z', $\tilde{\chi}_1^0 - \tilde{\chi}_6^0$, D

$\diamond$ $E_6 \supset SO(10) \times U(1)_\psi \supset SU(5) \times U(1)_\chi \times U(1)_\psi$

At the electroweak scale, $Z' = \cos\theta_E Z_\chi + \sin\theta_E Z_\psi$

the χ-model for $\theta_E = 0$, the ψ-model for $\theta_E = \pi/2$, the ν-model for $\theta_E = \tan^{-1}\sqrt{15}$, the η-model for $\theta_E = \tan^{-1}(-\sqrt{5/3})$.

- Explicit Breaking of the global $U(1)$ Peccei-Quinn (PQ) Symmetry

$\longleftarrow$ in order to escape a massless pseudoscalar Higgs boson (axion) at the tree level

NMSSM: Cubic term of N; $\sim kA_k N^3/3$

USSM: Breaking terms of $U(1)'$ gauge symmetry in terms of VEV of the Higgs singlet (S) at a TeV scale, $m_{Z'} \approx 1-2$ TeV:

$$\sim \frac{{g'_1}^2}{2}(\tilde{Q}_1|H_1|^2 + \tilde{Q}_2|H_2|^2 + \tilde{Q}_3|S|^2)^2$$

We take the η-model, where $\theta_E = \tan^{-1}(-\sqrt{5/3})$

In the η-model, $\tilde{Q}_i = Q_i^\eta + \delta Q_i^Y$.

The kinetic mixing parameter is defined by $\delta = g_{11}/g'_1$, where g_{11} is a new gauge coupling constant arising from the mixing between g_1 and g'_1.

2. The Higgs sector of the Non-MSSMs

(a) The Next-to-MSSM (NMSSM)

SUSY08

⊙ **Higgs bosons in the NMSSM and other extensions of the MSSM (Plenary), John Gunion**

⊙ **The constraint NMSSM: mSUGRA and GMSB (Plenary), Ulrich Ellwanger**

⊙ **Light Charged and CP-odd Higgses in MSSM-like Models at** $\tan\beta \simeq 1$ **(Parallel), Radovan Dermisek**

⊙ **Possible lepton universality breaking in Upsilon decays in the NMSSM (Parallel), Sanchis-Lozano Miguel**

- **Higgs Bosons in a Nonminimal Supersymmetric Model, J. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski, F. Zwirner, PRD39, 844 (1989)**
- **Radiative corrections to the neutral Higgs spectrum in supersymmetry with a gauge singlet, U. Ellwanger, PLB303, 271 (1993)**

$$\begin{aligned} H_1 &= \begin{pmatrix} v_1 + S_1 + i\sin\beta P_1 \\ \sin\beta C^{+*} \end{pmatrix} , \quad H_2 = \begin{pmatrix} \cos\beta C^{+} \\ v_2 + S_2 + i\cos\beta P_1 \end{pmatrix} , \\ N &= \left(x + S_3 + iP_2 \right) . \end{aligned}$$

Superpotential:

$$W = h_t Q H_2 t_R^c + h_b Q H_1 b_R^c + \lambda N H_1 H_2 + \frac{k}{3} N^3$$

$$\begin{aligned} V &= V_D + V_F + V_{\mathrm{S}} + \sum_l \frac{n_l \mathcal{M}_l^4}{64\pi^2} \left[\log \frac{\mathcal{M}_l^2}{\Lambda^2} - \frac{3}{2} \right] , \\ V_D &= \frac{g_2^2}{8} (H_1^\dagger \vec{\sigma} H_1 + H_2^\dagger \vec{\sigma} H_2)^2 + \frac{g_1^2}{8} (|H_2|^2 - |H_1|^2)^2 , \\ V_F &= |\lambda|^2 [(|H_1|^2 + |H_2|^2)|N|^2 + |H_1 H_2|^2] + |k|^2 |N|^4 - (\lambda k^* H_1 H_2 N^{*2} + \mathrm{H.c.}) , \\ V_{\mathrm{S}} &= m_{H_1}^2 |H_1|^2 + m_{H_2}^2 |H_2|^2 + m_N^2 |N|^2 - (\lambda A_\lambda H_1 H_2 N + \frac{1}{3} k A_k N^3 + \mathrm{H.c.}) . \end{aligned}$$

(b) The $U(1)$-extended Supersymmetric Standard Model (USSM)
Superpotential:

$$W \approx h_t Q H_2 t_R^c + h_b Q H_1 b_R^c + \lambda S H_1 H_2 \ ,$$

$$V = V_D + V_F + V_{\rm S} + V_1 \ ,$$

$$\begin{aligned} V_D &= \frac{g_2^2}{8}(H_1^\dagger \vec{\sigma} H_1 + H_2^\dagger \vec{\sigma} H_2)^2 + \frac{g_1^2}{8}(|H_1|^2 - |H_2|^2)^2 \\ &\quad + \frac{g_1'^2}{2}(\tilde{Q}_1 |H_1|^2 + \tilde{Q}_2 |H_2|^2 + \tilde{Q}_3 |S|^2)^2 \ , \\ V_F &= |\lambda|^2 [(|H_1|^2 + |H_2|^2)|S|^2 + |H_1 H_2|^2] \ , \\ V_{\rm S} &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_3^2 |S|^2 - [\lambda A_\lambda (H_1 H_2) S + {\rm H.c.}] \ , \\ V_1 &= \sum_l \frac{n_l \mathcal{M}_l^4}{64\pi^2} \left[\log \frac{\mathcal{M}_l^2}{\Lambda^2} - \frac{3}{2}\right] \ , \end{aligned}$$

The $U(1)'$ gauge invariance condition: $\tilde{Q}_1 + \tilde{Q}_2 + \tilde{Q}_3 = 0$

In the USSM,

$$\begin{aligned}
\phi &= \frac{1}{2}\tan^{-1}\left(\frac{2\Delta^2}{m_{Z'}^2 - m_Z^2}\right) \ , \\
m_Z^2 &= (g_1^2 + g_2^2)v^2/2 \ , \\
m_{Z'}^2 &= 2{g'_1}^2 v^2(\tilde{Q}_1^2\cos^2\beta + \tilde{Q}_2^2\sin^2\beta) + 2{g'_1}^2 s^2 \tilde{Q}_3^2 \ , \\
\Delta^2 &= \sqrt{g_1^2 + g_2^2}\, g'_1 v^2(\tilde{Q}_1\cos^2\beta - \tilde{Q}_2\sin^2\beta) \ ,
\end{aligned}$$

Experimental Constraints on $m_{Z'}$ and ϕ:

In the η model (Review of Particle Physics),

$m_{Z'} > 745$ **GeV (**$p\bar{p}$ **direct search)**

$m_{Z'} > 619$ **GeV (electroweak fit)**

$|\phi| < 2 - 3 \times 10^{-3}$ **(precision measurements)**

In the η-model, $\tilde{Q}_i = Q_i^\eta + \delta Q_i^Y$.

When $\delta = 1/3$, Z' does not couple charged leptons and Z' becomes leptophobic. If the Z' is leptophobic, the Z' mass can be as small as 100 GeV and the mixing angle ϕ can be as large as 0.06.

- G. C. Cho, K. Hagiwara, Y. Umeda, NPB531, 65, (1998).

Thus, the VEV of the Higgs singlet can be as small as $s = 700$ GeV.

- Neutral scalar Higgs bosons in the USSM at the LHC, S. W. Ham, Taeil Hur, P. Ko, S. K. Oh, hep-ph/0801.2361; In the USSM

$$m_{S_1}^2 \leq \lambda^2 v^2 \sin^2 2\beta + m_Z^2 \cos^2 2\beta + 2{g'_1}^2 v^2 (\tilde{Q}_1 \cos^2\beta + \tilde{Q}_2 \sin^2\beta)^2 + \Delta m_{S_1}^2 \ .$$

In the leptophobic η model, $m_{S_1} \leq 162$ GeV, for $1 < \tan\beta \leq 30$, $0 < \lambda \leq 0.85$, $700 \leq s \leq 2000$ GeV and $g'_1 = g_1$.

- Higgs bosons of a supersymmetric $U(1)'$ model at the International Linear Collider, S. W. Ham, E. J. Yoo, S. K. Oh, and D. Son, PRD77, 114011 (2008)

In the USSM, G_{ZZS_i} $(i = 1, 2, 3)$.

In the SM, $G_{ZZH} = g_2 m_Z / \cos\theta_W$.

We normalize G_{ZZS_i} by G_{ZZH} such that $\bar{G}_{ZZS_i} = G_{ZZS_i}/G_{ZZH}$.

The normalized scalar-Higgs couplings to ZZ:

$$
\begin{aligned}
\bar{G}_{ZZS_i}(\phi) &= \cos\beta O_{1i} {C_1}^2 + \sin\beta O_{2i} {C_2}^2 + \frac{s O_{3i}}{4 G_{ZZH}} {C_3}^2 \ , \\
C_1 &= \cos^2\theta_W + \sin^2\theta_W \cos\phi - \frac{g_1' \tilde{Q}_1}{g_2} \cos\theta_W \sin\theta_W \sin\phi \ , \\
C_2 &= \cos^2\theta_W + \sin^2\theta_W \cos\phi + \frac{g_1' \tilde{Q}_2}{g_2} \cos\theta_W \sin\theta_W \sin\phi \ , \\
C_3 &= g_1' \tilde{Q}_3 \sin\theta_W \sin\phi \ .
\end{aligned}
$$

If $\phi = 0$**,** $C_1 = C_2 = 1$**,** $C_3 = 0$**, and thus** $\bar{G}_{ZZS_i}(0) = \cos\beta O_{1i} + \sin\beta O_{2i}$**.**

In NMSSM, $\sum_{i=1}^{3} \bar{G}^2_{ZZS_i}(0) = 1$**;**

J. F. Gunion, B. Grzadkowski, H. E. Haber, J. Kalinowski, PRL79, 982 (1997) .

In the leptophobic η **model,**

$$1 \neq \sum_{i=1}^{3} \bar{G}^2_{ZZS_i}(\phi)$$

$$= \cos^2\beta C_1^4 + \sin^2\beta C_2^4 + \left(\frac{sC_3^2}{4G_{ZZH}}\right)^2$$

For $s = 700$ **GeV,** $|\phi| < 0.03 - 0.037$ **and** $644 < m_{Z'} < 650$ **GeV**

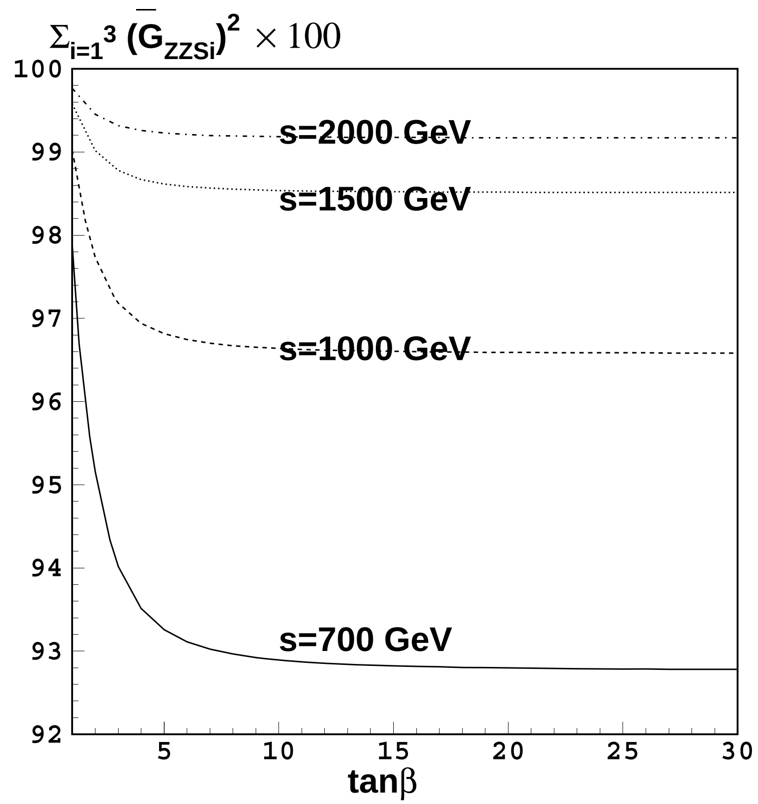

Fig. 1: $\sum_{i=1}^{3} \bar{G}^2_{ZZS_i}(\phi)$ against $\tan\beta$

We define

$$\Delta_i = \frac{|\bar{G}^2_{ZZS_i}(\phi) - \bar{G}^2_{ZZS_i}(0)|}{\bar{G}^2_{ZZS_i}(0)} \ .$$

For most of the parameter space,

Δ_i are about 7 %.

The result of Fig. 2 suggests that the scalar Higgs sector of the lepto-phobic η model can be distinguished from that of the NMSSM.

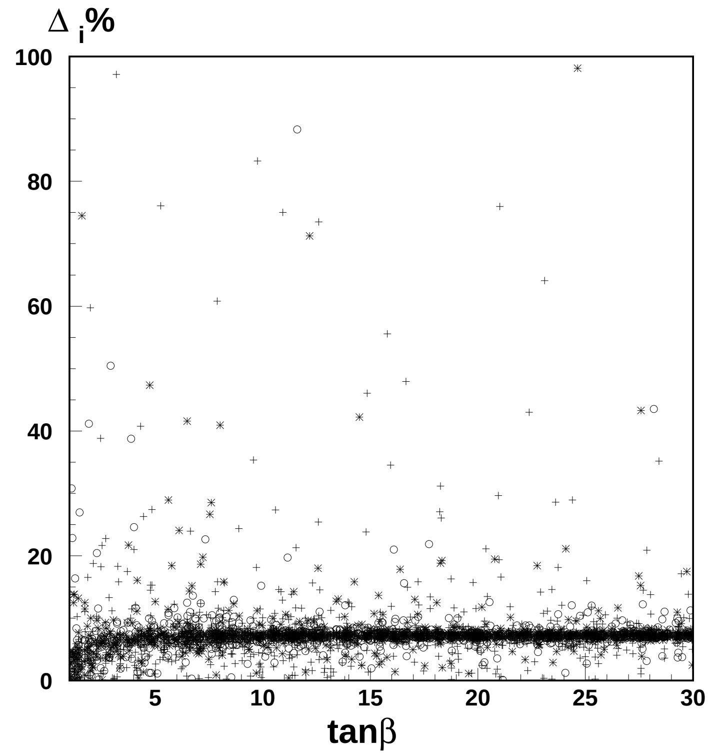

Fig. 2: Δ_i against $\tan\beta$ for $s = 700$ GeV, where parameter values are randomly varied within the allowed ranges. The points marked by star, circle, and cross are respectively Δ_1, Δ_2, and Δ_3.

At the ILC, the dominant Higgs channels are

(i) The Higgs-strahlung process $e^+e^- \to ZS_i$ **:** $\sigma_i^H(\phi)$

(ii) The WW **fusion process** $e^+e^- \to \bar{\nu}_e \nu_e S_i$ **:** $\sigma_i^W(\phi)$

(iii) The ZZ **fusion process** $e^+e^- \to e^+e^- S_i$ **:** $\sigma_i^Z(\phi)$

In the the leptophobic η **model,** $\sigma_i^H(\phi)$ **is related to the production cross section for the SM Higgs boson via the Higgs-strahlung process as**

$$\sigma_i^H(\phi) = (G_{ZZS_i}(\phi)/G_{ZZH})^2 \sigma_{\rm SM}^H = \bar{G}_{ZZS_i}^2(\phi)\sigma_{\rm SM}^H \ .$$

Likewise, we have $\sigma_i^Z(\phi) = \bar{G}_{ZZS_i}^2(\phi)\sigma_{\rm SM}^Z$ **for the** ZZ **fusion process.**

Meanwhile, $\bar{G}_{WWS_i}^W(\phi) = \bar{G}_{WWS_i}^W(0)$ **for the leptophobic** η **model.**

Since $G_{WWS_i}(0)/G_{WWH} = \bar{G}_{ZZS_i}(0)$**,** $\sigma_i^W(0) = \bar{G}_{ZZS_i}^2(0)\sigma_{\rm SM}^W$ **for the** WW **fusion process**

$\diamondsuit$ **In terms of** $\bar{G}^2_{ZZS_i}(0)$**, one may obtain** $\sigma_i^Z(0)$ **and** $\sigma_i^H(0)$**, which are the production cross sections of** S_i **in the NMSSM.**

$\diamondsuit$ **On the other hand, in terms of** $\bar{G}^2_{ZZS_i}(\phi)$**, one may also obtain** $\sigma_i^Z(\phi)$ **and** $\sigma_i^H(\phi)$**, which are the production cross sections of** S_i **in the leptophobic** η **model.**

$\odot$ **Such a situation is summarized in Table 1.**

TABLE: The masses, the normalized coupling to ZZ, and the production cross sections, for $\tan\beta = 10$, $m_Q = 500$ GeV, $\lambda = 0.35$, $A_t = 500$, and $m_p = 200$ GeV at the ILC with $\sqrt{s} = 800$ GeV. Those quantities with $\phi = 0$ are the NMSSM values, except for $\sigma_i^W(0)$, which are also the leptophobic η-model values: $\sigma_i^W(0) = \sigma_i^W(\phi)$.

i	m_{S_i} GeV	$\bar{G}^2_{ZZS_i}(\phi)$	$\bar{G}^2_{ZZS_i}(0)$	$\sigma_i^W(0)$ fb	$\sigma_i^H(\phi)$ fb	$\sigma_i^H(0)$ fb	$\sigma_i^Z(\phi)$ fb	$\sigma_i^Z(0)$ fb
1	140	0.9018	0.9699	62.68	18.02	19.38	6.362	6.843
2	201	0.0162	0.0185	0.620	0.297	0.336	0.060	0.068
3	295	0.0108	0.0114	0.103	0.156	0.166	0.010	0.011

All of the three scalar Higgs bosons are not so heavy and thus kinematically within the reach of the ILC.

3. Conclusions

[1] **In the leptophobic** η **model,** $m_{S_1} \leq 162$ **GeV.**

[2] **In the NMSSM,** $\sum_{i=1}^{3} \bar{G}^2_{ZZS_i}(0) = 1$**, whereas** $\sum_{i=1}^{3} \bar{G}^2_{ZZS_i}(\phi) < 1$ **in the the leptophobic** η **model . Thus, any discrepancy of the sum rule from unity would distinguish the leptophobic** η **model from the NMSSM.**

[3] **By comparing** $\bar{G}^2_{ZZS_i}(0)$ **with** $\bar{G}^2_{ZZS_i}(\phi)$ **in Table 1, finding a distinction between the leptophobic** η **model and the NMSSM would be possible.**

Thanks a lot