Neutral Higgs Boson Production and CP Violation at LC

Kang Young Lee
Department of Physics, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea

C.S. Kim, Chaehyun Yu
Department of Physics and IPAP, Yonsei University, Seoul 120-749, Korea

We study the neutral Higgs boson production at the $e^-e^+$ linear collider in the two Higgs doublet model with the CP violation. The CP-even and CP-odd scalars are mixed in this model, which affects the production process of neutral Higgs boson.

1 Introduction

Conventional wisdom is that the standard model (SM) is not the final theory but just an effective theory of a fundamental structure. The two Higgs-doublet (2HD) model is one of the simplest extensions of the SM, which consist of two SU(2) scalar doublets. A discrete symmetry is often introduced to avoid a dangerous flavour-changing neutral currents (FCNC) in the 2HD model, which forbids the CP violating terms in the Higgs potential. If we abandon the discrete symmetry, complex Higgs self-couplings exist in general, and consequently the explicit and spontaneous CP violation is allowed in the Higgs sector. In that case, Higgs-mediated FCNC are present at tree level and we must consider a way to suppress the FCNC, e.g. to assume an approximate flavour symmetry. Its phenomenological implications have been widely studied$^{1,2,3,4,5}$.

In this work, we focus on the Higgs-gauge sector in the general 2HD model with CP violation and study the neutral Higgs boson production at the $e^-e^+$ Linear Colliders (LC).

2 The Model

The general Higgs potential of the 2HD model is given by

$$V = \frac{1}{2} \lambda_1 (\phi^+_1 \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi^+_2 \phi_2)^2 + \lambda_3 (\phi^+_1 \phi_1)(\phi^+_2 \phi_2) + \lambda_4 (\phi^+_1 \phi_2)(\phi^+_2 \phi_1)$$

$$+ \frac{1}{2} [\lambda_5 (\phi^+_2 \phi_2)^2 + H.c.] + [\lambda_6 (\phi^+_1 \phi_1)(\phi^+_2 \phi_2) + \lambda_7 (\phi^+_2 \phi_2)(\phi^+_1 \phi_2) + H.c.]$$

$$- m_{11}^2 (\phi^+_1 \phi_1) - m_{22}^2 (\phi^+_2 \phi_2) - [m_{12}^2 (\phi^+_1 \phi_2) + H.c.].$$

(1)

$^a$Conference Speaker
where $\lambda_5, \lambda_6, \lambda_7$ and $m_{12}^2$ are complex and others are real. The discrete symmetry $\phi_1 \rightarrow -\phi_1$ or $\phi_2 \rightarrow -\phi_2$ leads to the absence of $m_{12}^2, \lambda_6$ and $\lambda_7$. Here, we allow soft violation of the discrete symmetry by the dimension 2 terms $m_{12}^2 \neq 0$ to introduce the CP violation.

The minimization of the potential at $\langle \phi_1 \rangle = (0, v_1)^T/\sqrt{2}$ and $\langle \phi_2 \rangle = (0, v_2 e^{i\xi})^T/\sqrt{2}$ yields the relation:

$$\text{Im}(m_{12}^2 e^{i\xi}) = v_1 v_2 \text{Im}(\lambda_5 e^{2i\xi}),$$

where $v_1^2 + v_2^2 = v^2 = 2m_W^2/g^2$ and $\xi$ is the relative phase between $v_1$ and $v_2$. By the rephasing invariance, we can choose $\xi = 0$ which indicates no spontaneous CP violation but the CP violation is entirely explicit. Then the parameter $\text{Im}(m_{12}^2)$ can be replaced by $\text{Im}(\lambda_5)$ which is the only CP violating parameter in this model.

The neutral states are defined by $G_0^0 = \sqrt{2}(\text{Im}\phi_0^1 \cos \beta + \text{Im}\phi_0^2 \sin \beta)$, $A_0^0 = \sqrt{2}(-\text{Im}\phi_0^1 \sin \beta + \text{Im}\phi_0^2 \cos \beta)$, $\phi_1 = \sqrt{2} \text{Re}\phi_0^1$, $\phi_2 = \sqrt{2} \text{Re}\phi_0^2$. The $3 \times 3$ mass matrix of neutral Higgs bosons $(\phi_1, \phi_2, A)$ is constructed, of which (1, 3) and (2, 3) elements are given by

$$M^2_{13} = -\frac{1}{2} \text{Im} \lambda_5 v^2 \sin \beta, \quad M^2_{23} = -\frac{1}{2} \text{Im} \lambda_5 v^2 \cos \beta,$$

where $\tan \beta = v_2/v_1$. Note that both $M^2_{13}$ and $M^2_{23}$ depend upon the parameter $\text{Im} \lambda_5$. These non-zero elements indicate mixing between the CP-even and CP-odd states and imply the manifest CP violation. We diagonalize the mass matrix by the orthogonal transformation

$$M^2 = \mathcal{R} M^2 \mathcal{R}^\dagger,$$

where the orthogonal matrix $\mathcal{R}$ is parametrized by 3 Euler angles $\theta_a, \theta_b, \theta_c$

$$\mathcal{R} = \begin{pmatrix} -c_b s_a & c_a c_b & s_b \\ c_a s_c + s_a s_b s_c & s_a c_c - c_a s_b s_c & c_b s_c \\ -s_a s_c + s_a s_b c_c & -s_a c_c - c_a s_b c_c & c_b c_c \end{pmatrix},$$

with $s_{a,b,c} = \sin \theta_{a,b,c}$ and $c_{a,b,c} = \cos \theta_{a,b,c}$. Hereafter we set $\alpha = \theta_a$ by convention. Then the physical states for neutral Higgs bosons $h_1, h_2, h_3$ are defined by $(h_1, h_2, h_3)^T = \mathcal{R}(\varphi_1, \varphi_2, A)^T$. The CP-odd state $A$ and CP-even states $\varphi_1, \varphi_2$ are no longer physical states and it indicates a manifest CP violation in the neutral Higgs sector.
3 The Scenarios

The phenomenology of Higgs-gauge sector is governed by the couplings of the Higgs bosons to gauge bosons. The generalized $h_i ZZ$ couplings are given by

$$h_1 ZZ \sim \sin(\beta - \alpha) \cos \theta_b,$$

$$h_2 ZZ \sim \cos(\beta - \alpha) \cos \theta_c - \sin(\beta - \alpha) \sin \theta_b \sin \theta_c,$$

$$h_3 ZZ \sim -\cos(\beta - \alpha) \sin \theta_c - \sin(\beta - \alpha) \sin \theta_b \cos \theta_c,$$

(6)

and the generalized $h_i h_j Z$ couplings given by

$$Z h_1 h_3 \sim \cos(\beta - \alpha) \cos \theta_c - \sin(\beta - \alpha) \sin \theta_b \sin \theta_c,$$

$$Z h_2 h_3 \sim -\sin(\beta - \alpha) \cos \theta_b,$$

$$Z h_2 h_3 \sim \cos(\beta - \alpha) \sin \theta_c + \sin(\beta - \alpha) \sin \theta_b \cos \theta_c,$$

(7)

which are normalized by the SM coupling $g m_Z / \cos \theta_W$.

If $\text{Im} \lambda_5 = 0$, the mass matrix is reduced to the CP conserving case, where the imaginary parts and real parts of neutral scalar fields decouple. This is corresponding to the case of $\theta_b = \theta_c = 0$ in the matrix $R$. In our general study, we consider other limiting cases which could be of interest. If we assume that $\theta_b \sim 0$ and $\theta_c \sim \pi/2$, $h_2$ is decoupled and identified with the CP-odd Higgs boson $A$. In the limit that $\theta_b \sim \theta_c \sim \pi/2$, $h_1$ is decoupled to be $A$. In both cases, the Higgs-gauge couplings $g h_{i ZZ}$ and $g h_{i h_j Z}$ go close to those of the CP conserving case. Thus these limiting cases are similar to the CP conserving case except that the CP-odd Higgs may be light.

More interesting scenario is obtained by taking the limit $\sin \theta_c \to 0$. In this case, the off-diagonal elements becomes $M_{13}^2 = s_c c_b s_b (m_3^2 - m_2^2)$, and $M_{23}^2 = -c_c c_b s_b (m_3^2 - m_2^2)$. Considering the ratio $M_{13}^2 / M_{23}^2$, we obtain $\tan \beta = -\tan \alpha$. Then the CP violating parameter $\text{Im} \lambda_5$ is directly related to $\theta_b$ and Higgs masses,

$$\text{Im} \lambda_5 = \sin 2\theta_b \frac{m_3^2 - m_2^2}{v^2}.$$  

(8)

If we additionally assume that $\sin \theta_b$ is close to 1, the lightest Higgs decouples to be the CP-odd Higgs and this limiting case may look like the CP conserving case since the CP-odd Higgs decouples. However we see that the ratio $g_{h_2 ZZ} / g_{h_3 ZZ} = 1 / \tan(\beta - \alpha)$ in this case while $g_{h ZZ} / g_{H ZZ} = \tan(\beta - \alpha)$ in the CP conserving case. It can be a signal to discriminate this scenario from the CP conserving model in the gauge-Higgs sector without manifest observation of the CP asymmetry.


4 Neutral Higgs Boson Production

The most promising channel for the neutral Higgs boson production at the LC is the Higgsstrahlung process $e^−e^+ \rightarrow Z h_i$. For the numerical analysis, we demand the following constraints on the model parameters $^7$: (1) the perturbativity on the quartic couplings, $\lambda_i/4\pi < 1$, (2) the ordering of Higgs masses, $m_1 < m_2 < m_3$. Figure 1 depicts the cross sections of $Z h_1$ and $Z h_2$ productions with respect to the CP violating parameter $\text{Im} \lambda_5$ when varying $\theta_b$ and $\theta_c$. The $\times$ marks denote the value of the CP conserving case and $\beta−\alpha$ is fixed to be $\pi/6$. The green line denotes that $\theta_c = \pi/6$, the blue line $\theta_c = \pi/4$, and the yellow line $\theta_c = \pi/3$. We note that the cross section can be far away from that of the CP conserving model even if $\text{Im} \lambda_5$ is close to 0.

In Fig. 2, we show the cross section for $e^−e^+ \rightarrow h_1 h_2$ process. It can play a role of the supplementary process for the $e^−e^+ \rightarrow Z h_1$ channel since the $Z h_1 h_2$ coupling becomes large when $ZZh_1$ coupling vanishes $^8$.

5 Concluding Remarks

The neutral Higgs boson production processes, $e^−e^+ \rightarrow Z h_i$ and $e^−e^+ \rightarrow h_i h_j$ at the LC has been explored in the context of the two Higgs-doublet model with CP violation. We find that remarkably different phenomenology of the CP violating model is possible in the neutral Higgs boson production at the LC without direct CP violating signal.
References

1. Y.-L. Wu and L. Wolfenstein, Phys. Rev. Lett. 73, (1994) 1762; Phys. Rev. Lett. 73, (1994) 2809.
2. L. J. Hall and S. Weinberg, Phys. Rev. D 48, (1993) 979.
3. K. Y. Lee and J. K. Kim, Mod. Phys. Lett. A 10, (1995) 1761; A. Rasin and J. P. Silva, Phys. Rev. D 49, (1994) 20.
4. J.-F. Cheng, C.-S. Huang, and X.-h. Wu, Phys. Lett. B 585, (2004) 287; Y.-B. Dai, C.-S. Huang, J.-T. Li, W.-J. Li, Phys. Rev. D 67, (2003) 096007.
5. W. Khater and P. Osland, Nucl. Phys. B661, (2003) 209; G. Erkol, and G. Turan, Nucl. Phys. B635, (2002) 286.
6. I. F. Ginzburg and M. Krawczyk, hep-ph/0408011; I. F. Ginzburg, M. Krawczyk, and P. Osland, hep-ph/0211371; I. F. Ginzburg et al., hep-ph/0201117.
7. W. Khater and P. Osland, Acta Phys. Pol. B 34 (2003) 4531.
8. J. F. Gunion et al., Phys. Rev. Lett. 79, (1997) 982; B. Grzadkowski, J. F. Gunion, and J. Kalinowski, Phys. Rev. D 60, (1999) 075011.