Electroweak Baryogenesis and the Triple Higgs Boson Coupling

Shinya Kanemura
Osaka University, Toyonaka, Osaka 560-0043, Japan
Yasuhiro Okada and Eibun Senaha
KEK, Tsukuba, Ibaraki 305-0801, Japan

We study collider signatures of electroweak baryogenesis in the two Higgs doublet model and the minimal supersymmetric standard model. It is found that the trilinear coupling of the lightest Higgs boson receive large quantum corrections if the electroweak phase transition is strongly first order for successful baryogenesis. In the two Higgs doublet model, the magnitude of the deviation from the standard model value is shown to be larger than 10%. Such a deviation can be detected at a future electron-positron linear collider.

1. INTRODUCTION

The Higgs boson is responsible for the spontaneous breakdown of the electroweak symmetry, which leads to masses for the gauge bosons and quarks/leptons. The direct search of the Higgs boson at the LEP and various electroweak observable data indicate that the mass of the standard model (SM) Higgs boson is larger than 114 GeV [1] and less than 285 GeV [2]. Such a light Higgs boson can be discovered at the CERN LHC. The profile of the Higgs boson is expected to be throughly determined at the international Linear Collider (ILC) as well as the LHC. At the ILC, the Higgs couplings to the gauge bosons and the heavy fermions (b quark, τ lepton) can be measured with high accuracy, and determination of the triple Higgs boson coupling is expected to be $\mathcal{O}(10-20)\%$ level [3]. The high energy collider experiments will not only reveal the particle physics at the TeV scale, but also open the window to cosmological connection to particle physics, such as dark matter and bayogenesis.

In this talk, we focus on a collider signature of electroweak baryogenesis [4]. It is observed that the ratio of the baryon number density to entropy density is $n_B/s \sim 10^{-10}$ [5]. According to the Sakharov's criteria [6], there are three requirements for generation of the baryon asymmetry: (a) baryon number violation, (b) C and CP violation, and (c) deviation from thermal equilibrium. It is well known that the condition (c) is not satisfied in the SM with the current Higgs mass bound, and that the CP violating phase in the Kobayashi-Maskawa matrix is too small to generate the sufficient baryon asymmetry. Here, we consider electroweak baryogenesis in the two Higgs doublet model (2HDM) [7–10] and the minimal supersymmetric standard model (MSSM) [11]. In particular, we study a relationship between the strength of the electroweak phase transition and the quantum corrections to the trilinear coupling of the lightest Higgs boson.

2. ELECTROWEAK PHASE TRANSITION IN THE 2HDM

The 2HDM is a simple extension of the SM by adding the second Higgs doublet. In this model, the Z_2 symmetry ($\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2$) is imposed on the Yukawa interactions to avoid the tree-level Higgs-mediated flavor changing neutral current processes [12]. Consequently, the Higgs potential at the tree-level takes the form

$$\begin{aligned} V(\Phi_1,\Phi_2) \;=\; & m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ & + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\Big[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\Big], \end{aligned} \tag{1}$$

where m_3^2 or λ_5 can be complex. Here, we assume that their phases are small and neglect them at the first approximation. To simplify our analysis we consider the phase transition in the direction of $\langle\Phi_1\rangle = \langle\Phi_2\rangle = (0\ \varphi)^T/2$, which corresponds to $m_1 = m_2,\ \lambda_1 = \lambda_2$, in other words, $\sin(\beta-\alpha) = \tan\beta = 1$ [8, 9].

The one-loop contributions to the effective potentials at zero and finite temperatures [13] are respectively given by

$$V_1(\varphi) = n_i \frac{m_i^4(\varphi)}{64\pi^2}\left(\log\frac{m_i^2(\varphi)}{Q^2} - \frac{3}{2}\right), \quad V_1(\varphi, T) = \frac{T^4}{2\pi^2}\Big[\sum_{i=\text{bosons}} n_i I_B(a^2) + n_t I_F(a^2)\Big], \tag{2}$$

with

$$I_{B,F}(a^2) = \int_0^\infty dx\ x^2 \log\left(1 \mp e^{-\sqrt{x^2+a^2}}\right), \quad a(\varphi) = \frac{m(\varphi)}{T}, \tag{3}$$

where Q is a renormalization scale, $m_i(\varphi)$ is the field dependent mass of the particle i, and n_i is the degrees of the freedom of i, i.e., $n_W = 6,\ n_Z = 3$ for gauge bosons $(W^\pm,\ Z)$, $n_t = -12$ for top quark(t) and $n_h = n_H = n_A = 1,\ n_{H^\pm} = 2$ for the five physical Higgs bosons $(h, H, A, H^\pm)$.

The qualitative features of the phase transition can be understood by the following high temperature expansion. When $m_\Phi^2 \gg m_h^2,\ M^2$ $(\Phi \equiv H, A, H^\pm,\ M^2 \equiv m_3^2/\sin\beta\cos\beta)$, the field dependent masses of the heavy Higgs bosons can be written as $m_\Phi^2(\varphi) \simeq m_\Phi^2\varphi^2/v^2$. At high temperatures, the Higgs potential can be expanded in powers of φ [14].

$$V_{\text{eff}} \simeq D(T^2 - T_0^2)\varphi - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots, \tag{4}$$

where $E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_H^3 + m_A^3 + 2m_{H^\pm}^3)$. The non-zero E makes the phase transition first order. In order to preserve the generated baryon asymmetry, the sphaleron process must decouple after the phase transition. This condition gives [15]

$$\frac{\varphi_c}{T_c} \gtrsim 1, \tag{5}$$

where φ_c is the vacuum expectation value of the Higgs boson at the critical temperature T_c. One can easily see

$$\varphi_c = \frac{2ET_c}{\lambda_{T_c}}, \tag{6}$$

where λ_{T_c} is the quartic coupling at T_c. Due to the contributions of the heavy Higgs bosons in the loop, the first order phase transition can be strong enough to satisfy Eq. (5). The high temperature expansion makes it easy to see the phase transition analytically. However, it breaks down when the masses of the particles in loops become larger than T_c. In the following, we therefore calculate T_c and φ_c numerically.

3. RADIATIVE CORRECTIONS TO THE TRILINEAR COUPLING

We also calculate the trilinear coupling of the lightest Higgs boson (the hhh coupling) at zero temperature in the parameter region where the phase transition is strongly first order. The leading contribution of the heavy Higgs bosons and the top quark to the hhh coupling can be extracted from the one-loop calculation by [16]

$$\begin{aligned}&\lambda_{hhh}^{\text{eff}}(\text{2HDM}) \\ &\simeq \frac{3m_h^2}{v}\left[1 + \frac{m_H^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_H^2}\right)^3 + \frac{m_A^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_A^2}\right)^3 + \frac{m_{H^\pm}^4}{6\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_{H^\pm}^2}\right)^3 - \frac{m_t^4}{\pi^2 m_h^2 v^2}\right].\end{aligned} \tag{7}$$

It is easily seen that the effects of the heavy Higgs boson loops are enhanced by m_Φ^4 $(\Phi = H, A, H^\pm)$ when M^2 is zero. These effects do not decouple in the large mass limit $m_\Phi \to \infty$ and yields the large deviation of the hhh coupling from the SM prediction. In this case, m_Φ is bounded from above by perturbative unitarity ($m_\Phi \lesssim 550$ GeV) [17]. We note that when such nondecoupling loop effects due to the extra heavy Higgs bosons are large on the hhh coupling, the coefficient E of the cubic term in Eq (4) becomes large in this model. Therefore there is a strong correlation between the large quantum correction to the hhh coupling and successful electroweak baryogenesis.

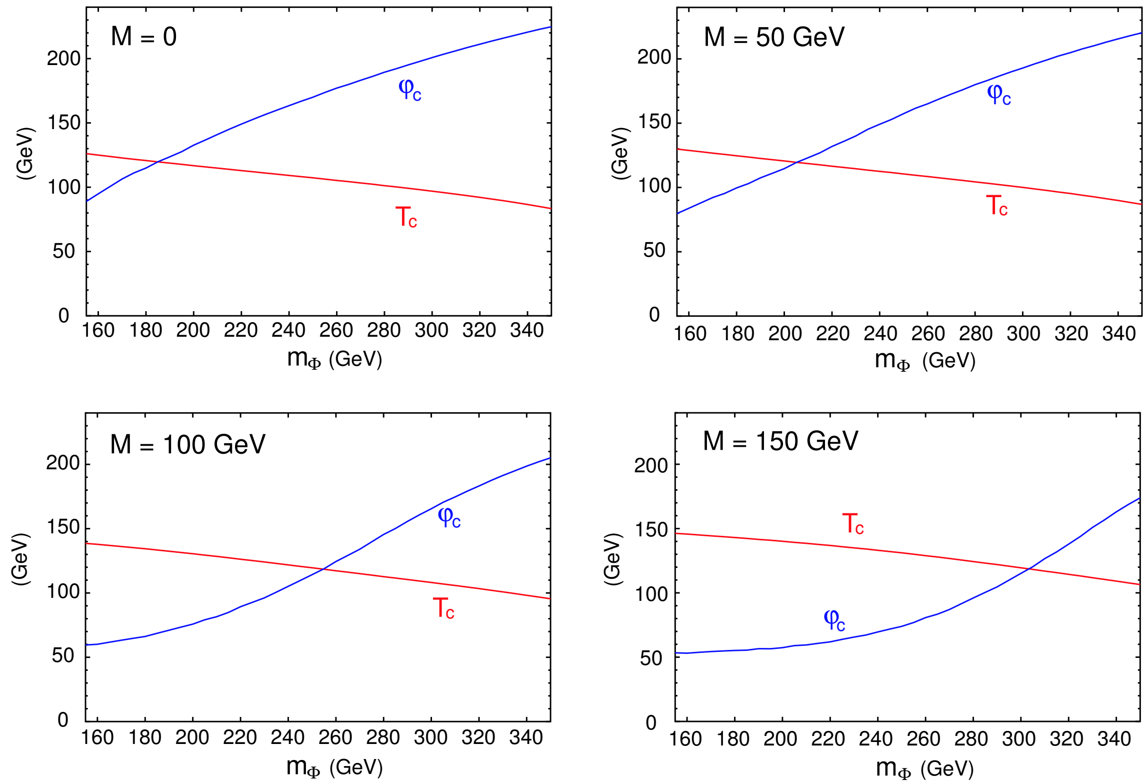

Figure 1: The Higgs vacuum expectation value φ_c at the critical temperature T_c as a function of the heavy Higgs boson mass m_Φ ($m_\Phi = m_H = m_A = m_{H^\pm}$) for $M = 0$, 50, 100 and 150 GeV. Other parameters are fixed as $\sin(\alpha-\beta) = \tan\beta = 1$ and $m_h = 120$ GeV.

4. NUMERICAL EVALUATION

We calculate the effective potential (2) varying the temperature T and determine the critical temperature T_c of the first order phase transition and the expectation value φ_c at T_c. Figs. 1 show the T_c and φ_c as a function of the mass of the heavy Higgs boson m_Φ for $M = 0,\ 50,\ 100$ and 150 GeV. We take $\sin(\alpha-\beta) = -1$, $\tan\beta = 1$ and $m_h = 120$ GeV. For the heavy Higgs boson mass, we assume $m_H = m_A = m_{H^\pm} (\equiv m_\Phi)$ to avoid the constraint on the ρ parameter from the LEP precision data [18]. We also take into account the ring summation for the contribution of the Higgs bosons to the effective potential at finite temperature to improve our calculation [13, 19]. In the case of $M = 0$, it is found that $\varphi_c = T_c \simeq 120$ GeV at $m_\Phi \simeq 185$ GeV, and the condition (5) is satisfied for $m_\Phi \gtrsim 185$ GeV. One can also find that the condition (5) can still be satisfied for $M = 150$ GeV, if the masses of the heavy Higgs bosons are greater than about 300 GeV.

In Figs. 2, we show the parameter region where the necessary condition of electroweak baryogenesis in Eq. (5) is satisfied in the m_Φ-M plane for $m_h = 100,\ 120,\ 140$ and 160 GeV. We also take $\sin(\alpha-\beta) = -1$ and $\tan\beta = 1$. For $m_h = 120$ GeV, we can see that the phase transition becomes strong enough for successful baryogenesis when the masses of the heavy Higgs bosons are larger than about 200 GeV. For the larger values of M or m_h, the greater m_Φ are required to satisfy the condition (5). In this figure we also plot the contour of the magnitude of the deviation in the hhh coupling from the SM value. We define the deviation $\Delta\lambda^{\rm 2HDM}_{hhh}/\lambda^{\rm eff}_{hhh}({\rm SM})$ by $\Delta\lambda^{\rm 2HDM}_{hhh} \equiv \lambda^{\rm eff}_{hhh}({\rm 2HDM}) - \lambda^{\rm eff}_{\rm hhh}({\rm SM})$. We calculated the deviation at the one loop level in the on-shell scheme which gives a better approximation than the formula given in Eq. (7) [16]. We can easily see that the magnitude of the deviation is significant ($\gtrsim 10\%$) in the parameter region where the electroweak baryogenesis is possible. Such magnitude of the deviation can be detected at a future LC experiment.

Next we discuss a scenario of electroweak baryogenesis in the MSSM. The strong first order phase transition can

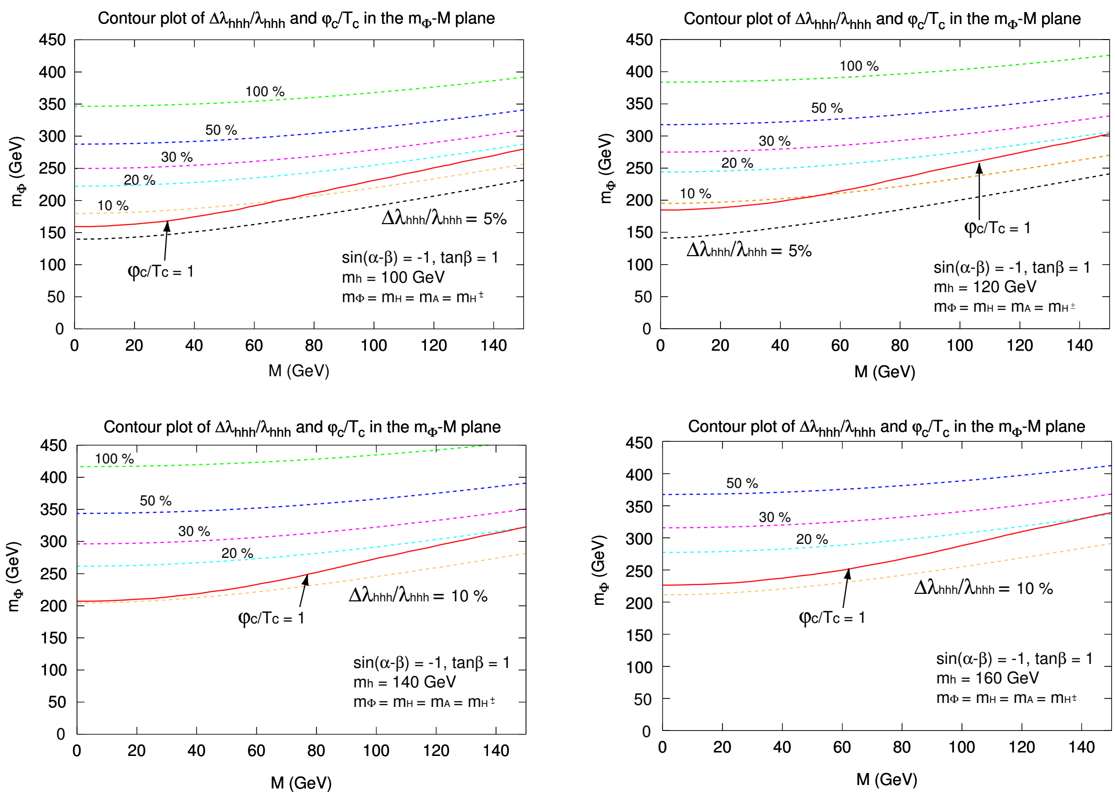

Figure 2: The contour of the radiative correction of the triple Higgs boson coupling constant overlaid with the line $\varphi_c/T_c = 1$ in the m_Φ-M plane for m_h=100, 120, 140 and 160 GeV. Other parameters are the same as those in Fig. 1. The above the critical line, the phase transition is strong enough for the successful electroweak baryogenesis scenario.

be induced by the loop effect of the light stop in the finite temperature effective potential [11]. We examine the loop effect of the light stop on the hhh coupling in this scenario. In the following, we only consider the finite and zero temperature effective potentials using high temperature expansion to understand the qualitative feature. As we have done in the case of the 2HDM, we consider the relationship between the magnitude of the phase transition and the deviation of the hhh coupling from the SM value. The combined result is approximately expressed as

$$\frac{\Delta\lambda_{hhh}(\mathrm{MSSM})}{\lambda_{hhh}(\mathrm{SM})} \simeq \frac{2v^4}{m_t^2 m_h^2}(\Delta E_{\tilde{t}_1})^2, \tag{8}$$

where m_h is the one-loop renormalized mass of the lightest Higgs boson and $\Delta E_{\tilde{t}_1}$ is the contribution of the light stop loop to the cubic term in the finite temperature effective potential. From the condition (5), the deviation in the hhh coupling from the SM value is estimated to be $\sim 6\%$ for $m_h = 120$ GeV. In the MSSM, the condition of the sphaleron decoupling also leads to the large deviation of the hhh coupling from the SM prediction at zero temperature.

In this talk, we have investigated that a phenomenological consequence of electroweak baryogenesis in the 2HDM and the MSSM. We found that the evidence of electroweak baryogenesis appears in the hhh coupling constant in both models. In the 2HDM, the magnitude of such a coupling constant can deviate from the SM prediction enough to be detected at the ILC.

Acknowledgments

The work of YO was supported in part by a Grant-in-Aid of the Ministry of Education, Culture, Sports, Science, and Technology, Government of Japan, Nos. 13640309, 13135225, and 16081211.

References

[1] R. Barate *et al.*, Phys. Lett. B **565** (2003) 61.

[2] The LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/.

[3] A. Djouadi, W. Kilian, M. Muhlleitner and P. M. Zerwas, Eur. Phys. J. C **10** (1999) 27; M. Battaglia, E. Boos and W. M. Yao, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. N. Graf, eConf **C010630** (2001) E3016 [hep-ph/0111276]; Y. Yasui, S. Kanemura, S. Kiyoura, K. Odagiri, Y. Okada, E. Senaha and S. Yamashita, in the Proceedings of International Conference on Linear Colliders (LCWS 2002), Jeju Island, Korea, August 26-30, 2002 [hep-ph/0211047]; S. Yamashita, talk given at LCWS 2004, April 2004.

[4] S. Kanemura, Y. Okada and E. Senaha, Phys. Lett. B **606**, 361 (2005). For reviews on electroweak baryogenesis, see A. G. Cohen, D. B. Kaplan and A. E. Nelson, Ann. Rev. Nucl. Part. Sci. **43** (1993) 27; M. Quiros, Helv. Phys. Acta **67** (1994) 451; V. A. Rubakov and M. E. Shaposhnikov, Usp. Fiz. Nauk **166** (1996) 493 [Phys. Usp. **39** (1996) 461]; K. Funakubo, Prog. Theor. Phys. **96** (1996) 475; M. Trodden, Rev. Mod. Phys. **71** (1999) 1463; W. Bernreuther, Lect. Notes Phys. **591** (2002) 237.

[5] H. V. Peiris *et al.*, Astrophys. J. Suppl. **148** (2003) 213.

[6] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32 [JETP Lett. **5** (1967 SOPUA,34,392-393.1991 UFNAA,161,61-64.1991) 24].

[7] N. Turok and J. Zadrozny, Phys. Rev. Lett. **65** (1990) 2331; N. Turok and J. Zadrozny, Nucl. Phys. B **358** (1991) 471; A. I. Bochkarev, S. V. Kuzmin and M. E. Shaposhnikov, Phys. Rev. D **43** (1991) 369; A. E. Nelson, D. B. Kaplan and A. G. Cohen, Nucl. Phys. B **373** (1992) 453; P. Huet and A. E. Nelson, Phys. Lett. B **355** (1995) 229; P. Huet and A. E. Nelson, Phys. Rev. D **53** (1996) 4578.

[8] A. I. Bochkarev, S. V. Kuzmin and M. E. Shaposhnikov, Phys. Lett. B **244** (1990) 275; N. Turok and J. Zadrozny, Nucl. Phys. B **369** (1992) 729.

[9] J. M. Cline, K. Kainulainen and A. P. Vischer, Phys. Rev. D **54** (1996) 2451.

[10] K. Funakubo, A. Kakuto, S. Otsuki, K. Takenaga and F. Toyoda, Prog. Theor. Phys. **94** (1995) 845; K. Funakubo, A. Kakuto, S. Otsuki and F. Toyoda, Prog. Theor. Phys. **96** (1996) 771.

[11] M. Carena, M. Quiros and C. E. M. Wagner, Phys. Lett. B **380** (1996) 81: D. Delepine, J. M. Gerard, R. Gonzalez Felipe and J. Weyers, Phys. Lett. B **386** (1996) 183.

[12] S. L. Glashow and S. Weinberg, Phys. Rev. D **15** (1977) 1958.

[13] L. Dolan and R. Jackiw, Phys. Rev. D **9** (1974) 3320.

[14] G. W. Anderson and L. J. Hall, Phys. Rev. D **45** (1992) 2685; M. Dine, R. G. Leigh, P. Y. Huet, A. D. Linde and D. A. Linde, Phys. Rev. D **46** (1992) 550.

[15] G. D. Moore, Phys. Lett. B **439** (1998) 357; G. D. Moore, Phys. Rev. D **59** (1999) 014503.

[16] S. Kanemura, S. Kiyoura, Y. Okada, E. Senaha and C. P. Yuan, Phys. Lett. B **558**, 157 (2003); S. Kanemura, Y. Okada, E. Senaha and C. P. Yuan, Phys. Rev. D **70**, 115002 (2004).

[17] S. Kanemura, T. Kubota and E. Takasugi, Phys. Lett. B **313** (1993) 155; A. G. Akeroyd, A. Arhrib and E. M. Naimi, Phys. Lett. B **490** (2000) 119.

[18] S. Eidelman *et al.* [Particle Data Group Collaboration], Phys. Lett. B **592** (2004) 1.

[19] P. Fendley, Phys. Lett. B **196** (1987) 175; M. E. Carrington, Phys. Rev. D **45** (1992) 2933; R. R. Parwani, Phys. Rev. D **45** (1992) 4695 [Erratum-ibid. D **48** (1993) 5965]; P. Arnold, Phys. Rev. D **46** (1992) 2628; P. Arnold and O. Espinosa, Phys. Rev. D **47** (1993) 3546 [Erratum-ibid. D **50** (1994) 6662]; J. R. Espinosa, M. Quiros and F. Zwirner, Phys. Lett. B **291** (1992) 115.