NEW PHYSICS FROM HIGGS SELF-COUPLING MEASUREMENT

SHINYA KANEMURA\textsuperscript{a}, YASUHIRO OKADA\textsuperscript{b,c}, and EIBUN SENAHA\textsuperscript{b,c}

\textsuperscript{a}Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
\textsuperscript{b}Theory Group, KEK, Tsukuba, Ibaraki 305-0801, Japan
\textsuperscript{c}Department of Particle and Nuclear Physics, the Graduate University for Advanced Studies (SOKENDAI), Tsukuba, Ibaraki 305-0801, Japan

Radiative correction to the triple Higgs boson coupling is studied in the two Higgs doublet model in connection with the electroweak baryogenesis. It is shown that the one loop correction is large enough to be identified in future linear collider experiments, if the baryon number of the Universe is generated at the first order electroweak phase transition.

1 Introduction

Measurement of the triple Higgs boson coupling is one of the most important goals of the Higgs physics at a future $e^+e^-$ linear collider (LC) experiment. This would provide the first direct information on the Higgs potential that is responsible for electroweak symmetry breaking. The existence of the triple Higgs coupling is a characteristic feature of the spontaneous breaking of the electroweak symmetry in models with only weak-doublet Higgs fields, since there is no term with an odd number of scalar fields in the original Lagrangian. Experimentally, the triple Higgs ($hhh$) coupling is determined from the double Higgs production processes, $e^+e^- \rightarrow Zhh$ and $e^+e^- \rightarrow \nu\bar{\nu}hh$ (W fusion process). The precision of the coupling determination is estimated as about 20\% (10\%) at 500 GeV (1 TeV) LC with an integrated luminosity of 1 ab$^{-1}$.\textsuperscript{1}

In this talk, we discuss new physics effects on the $hhh$ coupling constant. In particular, we take a Two Higgs Doublet Model (THDM) as an example of physics beyond the Standard Model (SM), and consider relationship between the radiative correction to the $hhh$ coupling constant and the condition for successful electroweak baryogenesis. Details on the calculation are presented elsewhere.\textsuperscript{2}

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2 Two Higgs Doublet Model and Electroweak Baryogenesis

Explaining the baryon-to-photon ratio of the Universe is a fundamental issue in the particle physics in connection with cosmology. Although the value is \( O(10^{-10}) \), it is not easy to create a sufficient baryon number from the baryon-number symmetric initial condition. In 1980’s, it was realized that the anomalous baryon number violation process becomes large at high temperature in the SM. This opened a possibility to generate a correct baryon number at the electroweak phase transition.

In order to realize successful electroweak baryogenesis, the electroweak phase transition has to be strong first order. In addition, effects of CP violation should be large enough to generate some charge flow across the expanding bubble wall that separates the broken and unbroken phases during the phase transition. In the minimal SM, it is known that a sufficient baryon number cannot be generated, because the phase transition is not of the first order and the effect of CP violation due to the Kobayashi-Maskawa phase is far too small. Therefore the Higgs sector should be extended for electroweak baryogenesis.

We consider the THDM as a viable model for the electroweak baryogenesis. The tree-level Higgs potential of the THDM is given by

\[
V_{\text{tree}} = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - (m_3^2 \Phi_1^* \Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2} |\Phi_1|^4 \\
+ \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^* \Phi_2|^2 + \left[ \frac{\lambda_5}{2} (\Phi_1^* \Phi_2)^2 + \text{h.c.} \right].
\]

(1)

In order to simplify the analysis of the electroweak phase transition, we focus on the case with \( m_1 = m_2 \) and \( \lambda_1 = \lambda_2 \), which is translated to the relation \( \sin(\beta - \alpha) = \tan \beta = 1 \) for the neutral Higgs and vacuum mixing angles. In this case, a relevant direction of the electroweak phase transition can be reduced to one complex dimension, and we calculate the finite temperature effective potential for this direction (\( \varphi \)).

The condition for the strong first order phase transition is expressed as

\[
\frac{\varphi_c}{T_c} > 1,
\]

(2)

where \( \varphi_c \) is the vacuum expectation value at the critical temperature \( (T_c) \). This condition is required in order not to erase the created baryon number by the sphaleron process after the phase transition. Unlike the SM with the current Higgs-boson mass bound, the first order phase transition is possible in the THDM due to a large correction to the finite temperature effective potential from heavy Higgs boson loop diagrams. We can understand the qualitative
feature of the effective potential using the high temperature expansion in the case of \( M(\equiv m_3/\sqrt{\cos\beta\sin\beta}) = 0 \). In this case,

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

where the coefficient of the cubic term is given by \( E \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_H^3 + m_A^3 + 2m_{H^\pm}^3) \), and \( H, A, \text{and } H^\pm \) are the heavy extra Higgs bosons. Then, \( \varphi_c/T_c \) is given by \( 2E/\lambda_T \). In the case of the SM, the contribution from the heavy Higgs boson masses is missing, so that \( E \) is too small for a presently allowed value of the Higgs boson mass. On the other hand, the condition (2) can be satisfied for reasonable values of heavy Higgs boson masses in the THDM.

In the previous work, we have investigated radiative corrections to the \( hh\) coupling in the THDM. We found that the correction contains quartic terms of the heavy extra Higgs boson masses for \( M = 0 \) due to heavy Higgs loop diagrams. We therefore expect a large correction to the \( hh\) coupling when the above condition on the first order phase transition is satisfied.

### 3 Numerical Calculation

We evaluate the finite temperature effective potential and the one-loop corrected effective potential at zero temperature in the THDM. Since the high temperature expansion is not a good approximation if the heavy extra Higgs boson mass exceeds the critical temperature \( T_c \), we calculate the finite temperature potential numerically. We also include the improvement from the ring resummation. We determine \( T_c \) and the value of \( \varphi \) at \( T_c \). We also calculate the correction to the \( hh\) coupling constant at the zero-temperature. (The actual calculation is done using the on-shell renormalization scheme instead of the effective potential method). In order to satisfy the \( \rho \) parameter constraint on the THDM, we take all the heavy extra Higgs boson masses to be the same value \( (m_\Phi) \).

In figure 1, we show the contour plot of the correction to the triple Higgs coupling constant \( (\Delta \lambda_{hhh}/\lambda_{hhh}) \) in the \( (M, m_\Phi) \) space. We overlay the line of \( \varphi_c/T_c = 1 \) in this plot. The lightest Higgs boson mass \( (m_h) \) is taken to be 120 GeV. We can see that the correction is larger than about 10% in the case when the phase transition is strong enough for successful electroweak baryogenesis. Such size of the deviation from the SM prediction is within the reach of the measurement at a future LC.

In this talk, we have studied a possible impact on the LC physics from the scenario of electroweak baryogenesis. In order to satisfy the condition of the
strong first-order phase transition, the finite temperature effective potential has to receive a large correction in the THDM. At the same time, radiative corrections to the zero-temperature effective potential induce a measurable deviation in the $hhh$ coupling constant at a LC. For successful electroweak baryogenesis, we also need to include CP violation effects at the phase transition. Impacts of new CP phases to collider physics depend on details of the electroweak baryogenesis scenario, and will be discussed elsewhere.

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