Anomalous Higgs-top coupling pollution of the triple Higgs coupling extraction at a future high-luminosity electron-positron collider

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(Received 8 May 2015; published 2 November 2015)

One of the most challenging tasks for future high-luminosity electron-positron colliders is to extract Higgs triple coupling. It was proposed that this can be carried out via precisely measuring the cross section of ZH associated production up to 0.4%. In this paper, we examine the possible heavy pollution from Higgs-top anomalous coupling. Our numerical results show that the pollution is small for $\sqrt{s}_{e^+e^-} = 240$ GeV. However, for the higher-energy collider, the pollution is sizable, which should be taken into account. We further explore the possibility of measuring CP-violated Higgs-top coupling via the forward-backward asymmetry A_{FB} for the process $e^+e^- \to ZH$. The asymmetry can reach 0.7% which is comparable to the precision of cross-section measurement.

DOI: 10.1103/PhysRevD.92.094001 PACS numbers: 12.38.Bx

I. INTRODUCTION

A standard model–like Higgs boson [1] (denoted as H(125) in this paper) was discovered at the Large Hadron Collider (LHC) in 2012. In order to test the standard model (SM) and discover possible physics beyond the SM (BSM), it is crucial to measure the Higgs Yukawa couplings and Higgs self-couplings at the LHC and future high energy colliders. In the first run of the LHC, the CMS and ATLAS collaborations constrained $h\bar{t}t$ Yukawa coupling indirectly through the global fit, with a precision of 20% and 30%, respectively [2,3]. With 300/fb, Yukawa couplings can be measured up to 23%, 13%, and 14% for $h\bar{b}b$, $h\tau^+\tau^-$, and $h\bar{t}t$, respectively [4]. It was also proposed to measure the top Yukawa coupling via the associated Higgs boson production with a single top quark [5–11]. The Higgs self-coupling can be measured up to 50% at the LHC with 300/fb [4]. There are also extensive studies on measuring anomalous triple Higgs coupling directly at the LHC [12–16] and at future electron-positron colliders [17,18].

For the future high-luminosity electron-positron colliders, it is proposed to measure the Higgs self-coupling up to 28% for $\sqrt{s_{e^+e^-}} = 240$ GeV under the model-dependent assumption that only the Higgs self-coupling is modified [19]. The precision of the Higgs self-coupling can only be reached based on the precisely measured cross section of ZH associated production up to 0.4% [20]. Entering $e^+e^- \to ZH$ via loops, the triple Higgs coupling might be polluted heavily by other anomalous couplings, with the most likely candidate being the $h-Z-Z$ coupling which appears even at tree level. The first run results of LHC show that the HVV couplings including $h-Z-Z$ coupling are consistent with those in the SM [2,3]. The Higgs-top coupling contributes to the process $e^+e^- \to ZH$ via loops and is potentially important for triple Higgs coupling extraction. Actually, the full one-loop correction to $e^+e^- \to ZH$ in the SM was calculated about two decades ago [21–24]. In this paper we will focus on the anomalous Higgs-top coupling, especially its effects on the extraction of triple Higgs coupling.

This paper is arranged as follows. In Sec. II, we estimate the deviation of the cross section for the process $e^+e^- \to ZH$ arising from anomalous Higgs-top coupling and compare it to that from triple Higgs coupling. In Sec. III, we explore how to measure CP-violated Higgs-top coupling via the forward-backward asymmetry A_{FB} for the process $e^+e^- \to ZH$. The last section contains our conclusion and discussion.

II. POLLUTION FROM HIGGS-TOP ANOMALOUS COUPLING

In the SM, the process $e^+e^- \to ZH$ occurs at tree level and the Feynman diagram is shown in Fig. 1.

One way to measure the triple Higgs coupling is to produce the Higgs pair, provided that the center of mass

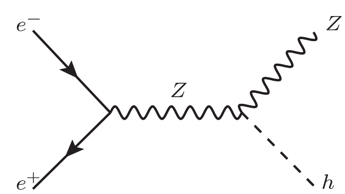

FIG. 1. Feyman diagram at tree level for the process $e^+e^- \to Zh$.

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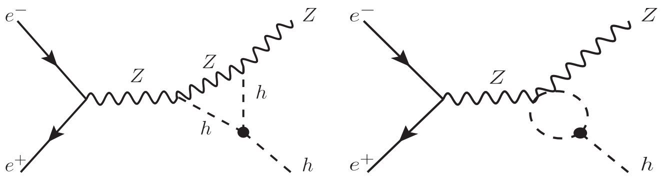

FIG. 2. Feynman diagram containing the anomalous $3h$ coupling, depicted as the black dot, at one-loop level for the process $e^+e^- \to Zh$.

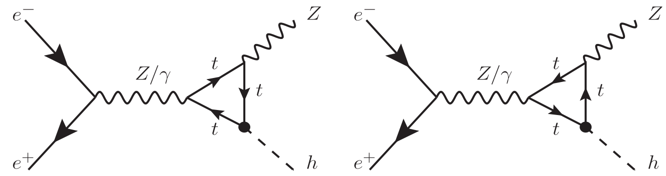

FIG. 3. Feynman diagram containing the anomalous $h\bar{t}t$ coupling, depicted as the black dot, at one-loop level for the process $e^+e^- \to Zh$.

energy of e^+e^- is high enough via $e^+e^- \to HHZ$ or $e^+e^- \to HH\nu\bar{\nu}$ [25]. For such processes, the cross sections are notorious small. High energy and high luminosity are both required. Another way to measure the triple Higgs coupling is via the virtual effects which are shown in Fig. 2. The capacity to measure the triple Higgs has been estimated by Ref. [19]. For completeness, we recalculate the analytical result for

$$\delta_\sigma \equiv \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{\delta_h \neq 0} - \sigma_{\delta_h = 0}}{\sigma_{\delta_h = 0}}$$

from the triple Higgs coupling $C_{\rm SM}(1+\delta_h)HHH = -3i\frac{m_h^2}{v}(1+\delta_h)HHH$ as

$$\delta_\sigma(3h) = \frac{3\alpha m_h^2 \delta_h}{16\pi\beta c_w^2 s_w^2 m_z^2}\mathrm{Re}[2\rho(C_1(m_h^2) + C_{11}(m_h^2) + C_{12}(m_h^2)) - \beta(B_0 - 4C_{00}(m_h^2) + 4m_z^2 C_0(m_h^2) + 3m_h^2 B_0')], \tag{1}$$

where $\delta_h = 0$ corresponds to the case in the SM. Here,

$$\beta = m_h^4 - 2m_h^2(m_z^2 + s) + m_z^4 + 10m_z^2 s + s^2,$$
$$\rho = (m_h^2 - m_z^2 - s)((m_h - m_z)^2 - s)((m_h + m_z)^2 - s).$$

The definition of the one-loop scalar functions B, C, etc. can be found in Ref. [26], and $C_0(m_h^2) = C_0(m_h^2, m_z^2, s, m_h^2, m_h^2, m_z^2)$, $C(m_h^2) = C(m_h^2, s, m_z^2, m_h^2, m_h^2, m_z^2)$, $B_0 = B_0(m_h^2, m_h^2, m_h^2)$, $B_0' = \frac{\partial B_0}{\partial p^2}|_{p^2 = m_h^2}$.

In this paper we will calculate the contributions from Higgs-top coupling which are shown in Fig. 3.[1] The Higgs-top coupling can be parametrized as

$$C_{\rm SM}(1+\delta_t)H\bar{t}t = -i\frac{m_t}{v}(1+\delta_t)H\bar{t}t,$$

where $\delta_t = 0$ corresponds to the case in the SM.

The analytical results can be written as

$$\begin{aligned}\delta_\sigma(htt) = {} & -\frac{4N_c\alpha m_t^2(s - m_z^2)v_1 v_2 \delta_t}{3\pi s\beta m_z^2(v_1^2 + a_1^2)}\mathrm{Re}[\beta(B_0(m_h^2) - 4C_{00}(m_t^2)) - 2\rho(C_1(m_t^2) + C_{11}(m_t^2) + C_{12}(m_t^2)) \\ & - 6m_z^2 s(s + m_z^2 - m_h^2)C_0(m_t^2)] + \frac{N_c\alpha m_t^2\delta_t}{\pi c_w^2 s_w^2 m_z^2\beta}\mathrm{Re}[\beta(2(v_2^2 + a_2^2)(B_0(m_h^2) - 4C_{00}(m_t^2)) + 2a_2^2(B_0(s) + B_0(m_z^2))) \\ & - \rho(4(v_2^2 + a_2^2)(C_1(m_t^2) + C_{11}(m_t^2) + C_{12}(m_t^2)) + 2a_2^2 C_2(m_t^2)) + ((v_2^2 + a_2^2)((4m_t^2 - m_z^2 - s)\beta - \rho) \\ & + (v_2^2 - a_2^2)(m_h^2 - 4m_t^2)\beta)C_0(m_t^2)] + \frac{N_c\alpha m_t^2\delta_t}{4\pi c_w^2 s_w^2 m_z^2}\mathrm{Re}[-B_0(m_h^2) + (4m_t^2 - m_h^2)B_0'(m_h^2)].\end{aligned} \tag{2}$$

In Eq. (2), the firsts, second, and third terms are from the contributions of the diagram with the photon propagator, Z boson propagator, and counter term of the ZZH vertex, respectively. Here $\alpha = \frac{e^2}{4\pi}$, $N_c = 3$, $v_1 = -\frac{1}{4} + s_w^2$, $a_1 = \frac{1}{4}$, $v_2 = \frac{1}{4} - \frac{2}{3}s_w^2$, $a_2 = -\frac{1}{4}$, $C_0(m_t^2) = C_0(m_h^2, m_z^2, s, m_t^2, m_t^2, m_t^2)$, $C(m_t^2) = C(m_h^2, s, m_z^2, m_t^2, m_t^2, m_t^2)$, $B_0(m_h^2) = B_0(m_h^2, m_t^2, m_t^2)$, $B_0(m_z^2) = B_0(m_z^2, m_t^2, m_t^2)$, and $B_0(s) = B_0(s, m_t^2, m_t^2)$.

We use LoopTools [27] to do the scalar integral for different c.m. energies. In Fig. 4, we show the deviation of the cross section arising from δ_t and δ_h as a function of $\sqrt{s}_{e^+e^-}$. Several numerical results for the typical c.m. energy are

$$\delta_\sigma^{240,350,400,500} = 1.45, 0.27, 0.05, -0.19 \times \delta_h\%, \tag{3}$$

$$\delta_\sigma^{240,350,400,500} = -0.49, 1.38, 2.14, 2.12 \times \delta_t\%. \tag{4}$$

The figures show that the behavior for δ_t and δ_h is opposite. At the low-energy end, the relative correction δ_σ happens to be dominated by δ_h; on the contrary, for the high-energy end, the δ_σ arising from the anomalous Higgs-top coupling cannot be neglected. For the proposed Circular Electron-Positron Collider with $\sqrt{s}_{e^+e^-} \simeq 240$ GeV, the

[1] In fact, the contributions from the $Z/\gamma - H$ bubble transition diagrams are zero.

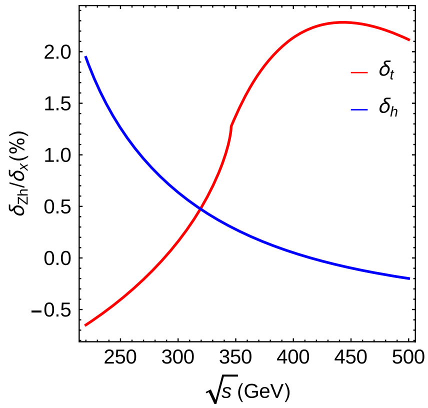

FIG. 4 (color online). Relative correction δ_σ due to anomalous $h\bar{t}t$ coupling δ_t (red) and anomalous triple Higgs coupling δ_h (blue), as a function of the e^+e^- c.m. energy from 220 to 500 GeV. Note that the precision of relative correction can reach 0.4% for high luminosity e^+e^- colliders.

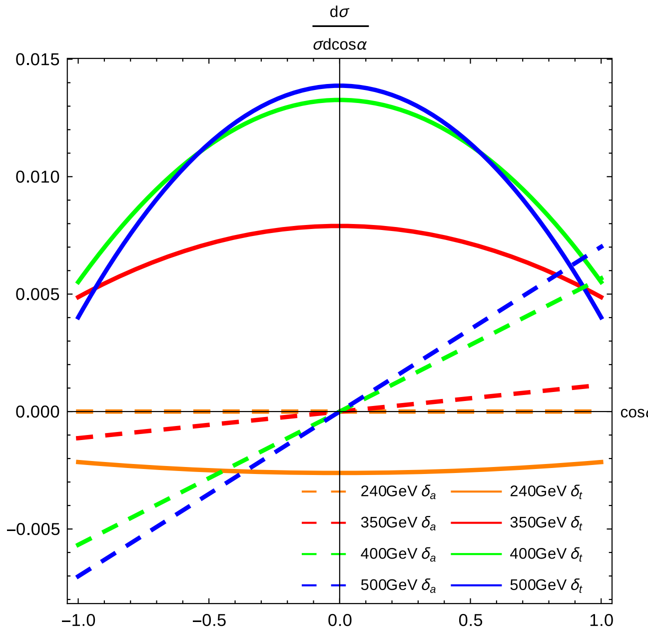

FIG. 5 (color online). Differential scattering cross section as a function of the scattering angle with $\sqrt{s} = 240$ (orange), 350 (red), 400 (green), and 500 GeV (blue). Solid and dashed lines stand for the contributions from δ_t and δ_a, respectively.

extraction of triple Higgs coupling is polluted by Higgs-top coupling. For the International Linear Collider with the option of high energy, the pollution from Higgs-top coupling must be taken into account.

III. MEASURING *CP*-VIOLATED HIGGS-TOP COUPLING

Though the newly discovered Higgs boson H(125) is SM-like, it does not exclude the possibility that H(125) is a *CP* mixing state. As has been emphasized by [28,29], the *CP* spontaneously broken [30] may be closely related to the lightness of the H(125). In fact, current measurements are insensitive to the mixing, especially for H decaying into gauge bosons since the *CP* violation usually enters the couplings via loops.

In this paper we parametrize the *CP* violation through

$$C_{\rm SM} H(1+\delta_t + i\delta_a\gamma_5) = -i\frac{m_t}{v} H(1+\delta_t + i\delta_a\gamma_5).$$

Indirect constraints on δ_t and δ_a at the LHC have been studied in [11]. At the 68% C.L. the allowed region for $(1+\delta_t, \delta_a)$ is a crescent with apex close to the SM point(1,0) [11]. The parameter space close to the SM point, namely $\delta_t \to 0$ and $\delta_a \to 0$, is allowed. At the same time, the parameter space with both nonzero δ_t, δ_a is also allowed. In fact, it is quite challenging for LHC to completely exclude the latter case via the indirect method. On the contrary, based on the last section analysis, the cross section deviation depends only on δ_t but not δ_a. This point will be made clear below. Therefore, it is important to explore the method to measure the δ_a at an electron-positron collider.

The analytical results for the differential cross section arising from δ_a can be written as

$$\frac{1}{\delta_a}\frac{d\sigma}{d\cos\alpha} = \frac{32 N_c a_1 m_t^2 \pi\alpha^3 \cos\alpha\sqrt{((m_h-m_z)^2-s)((m_h+m_z)^2-s)}}{c_w^4 s_w^4 (m_z^2 - s)} \times {\rm Im}\left[\frac{1}{3} v_2 C_0(m_t^2) + \frac{s}{c_w^2 s_w^2(m_z^2-s)} v_1((v_2^2+a_2^2)C_0(m_t^2) + 2a_2^2 C_2(m_t^2))\right]. \tag{5}$$

Here $\cos\alpha$ is the angle between the momentum of the electron and the Z boson. The differential cross section is proportional to $\cos\alpha$, which is due to the term $\varepsilon_{\mu\nu\rho\lambda}\varepsilon^{\mu\nu\alpha\beta} p_2^\rho p_1^\lambda k_{1\alpha} k_{2\beta}$, where p_1 p_2 are the momentum of the electron and positron and k_1 k_2 are the momentum of the Higgs and Z. Another critical requirement for nonvanishing contribution to the differential cross section is that there should be an imaginary part from the top loops. This requires that the $\sqrt{s}_{e^+e^-}$ must be greater than $2m_t$.

It is obvious that the *CP*-odd contribution to the total cross section is zero. In order to show the different contributions from δ_t and δ_a, respectively, we plot the normalized differential cross sections for several

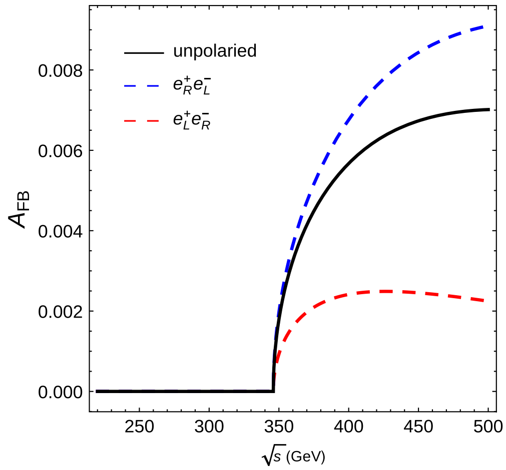

FIG. 6 (color online). A_{FB} as a function of $\sqrt{s}_{e^+e^-}$ from 220 to 500 GeV for polarized or unpolarized electron and positron beams. The black line, blue dashed, and red dashed separately correspond to unpolarized electron/positron beams and $e_R^+e_L^-$ and $e_L^+e_R^-$ polarizations.

$\sqrt{s}_{e^+e^-}$ and set the corresponding parameter δ_t or δ_a equal to 1. From the Fig. 5, it is quite clear that the differential cross sections arising from δ_t are symmetric and antisymmetric from δ_a. For $\sqrt{s} = 240$ GeV, the contribution from δ_a is zero because there is no imaginary part of $C_0(m_t^2)$. When $\sqrt{s}_{e^+e^-} > 2m_t$, there are nonzero contributions from δ_a as expected.

In order to gauge the forward-backward asymmetry, we introduce

$$A_{\mathrm{FB}} \equiv \frac{\int_0^1 d\cos\alpha \frac{d\sigma}{d\cos\alpha} - \int_{-1}^0 d\cos\alpha \frac{d\sigma}{d\cos\alpha}}{\sigma_{\mathrm{tot}}}.$$

In Fig. 6, we plot A_{FB} as a function of $\sqrt{s}_{e^+e^-}$ with $\delta_a = 1$ for polarized and unpolarized electron and positron beam. From the figure we can see that the asymmetry can reach 0.7% for $\sqrt{s}_{e^+e^-}$. Such precision is comparable to that of cross section measurement. It seems that the high luminosity collider is necessary.

IV. CONCLUSION AND DISCUSSION

In this paper, we explore the Higgs-top anomalous coupling pollution to the extraction of Higgs self-coupling via precisely measuring the cross section of $e^+e^- \to ZH$. The important conclusion is that the pollution is small for the $\sqrt{s}_{e^+e^-} = 240$ GeV but can be sizable for a higher-energy collider. The contributions to the total cross section from Higgs-top CP-odd coupling is vanishing, while such interaction can be scrutinized via forward-backward asymmetry for $\sqrt{s}_{e^+e^-}$ greater than $2m_t$.

ACKNOWLEDGMENTS

We would like to thank Shao Long Chen, Gang Li, and Pengfei Yin for the useful discussions. This work was supported in part by the Natural Science Foundation of China (Grants No. 11135003 and No. 11375014).

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