Direct searches of extra Higgs boson at future colliders

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We study direct searches of additional Higgs bosons in multi-top-quarks events at the LHC with the collision energy of 14 TeV as well as the International Linear Collider (ILC) with the collision energy of 1 TeV. As a benchmark model, we consider two Higgs doublet models with a softly-broken discrete $Z_2$ symmetry, where the $t\bar{t}$ decay mode of additional neutral Higgs bosons can be dominant if their masses are heavy enough. Thus, the multi-top-quarks events become an important probe of the extended Higgs sector at future colliders. We estimate the discovery reach at the LHC and the ILC, and find that the search at the ILC can survey the parameter regions where the LHC cannot cover.

I. INTRODUCTION

A Higgs boson was discovered at the LHC. Further measurements at the LHC have revealed its properties, such as its mass, spin-parity, and couplings to the standard model (SM) particles. At the present experimental precision, it seems quite consistent with the Higgs boson in the SM. The determination of the whole structure of the Higgs sector is an important task at future experiments, since various kinds of the Higgs sector are predicted in models for the physics beyond the SM (BSM). To explore the whole structure of the Higgs sector at collider experiments, two major approaches have been considered; the direct searches of second, third and even more Higgs bosons, and the indirect searches of the BSM effects through the deviations in the observed Higgs boson properties by precision measurements.

In general, it is argued that the direct searches are performed at the energy frontier experiments, such as the LHC, and the indirect searches are performed at the precision frontier experiments, such as the International Linear Collider (ILC) [2]. In this talk, we discuss the direct searches of additional Higgs bosons at the ILC [1, 3] in addition to the LHC, and their complementarity. We consider the two Higgs doublet model (2HDM) as a benchmark model of the extended Higgs sector. Especially, we focus on the heavy (neutral) Higgs bosons which predominantly decay into a $t\bar{t}$ pair resulting multi-top-quarks events as a signal of such Higgs bosons. We study the discovery potential of such events at the LHC and the ILC, and compare the parameter regions to be explored by the searches at these experiments. We find that the parameter regions to be explored at the LHC and the ILC are different, therefore, searches at the two experiments are complementary to survey the wider parameter regions in the extended Higgs sector.

II. TWO HIGGS DOUBLET MODEL

We consider the 2HDM as a benchmark model of the extended Higgs sector. The model has various phenomenologically plausible features, such that the electroweak rho parameter is preserved to be unity at the tree-level; sources of additional CP phases are provided; and additional four Higgs bosons are predicted. Under the assumption of the CP invariance in the Higgs sector for simplicity, these can be identified as CP-even $H$, CP-odd $A$, and a pair of charged $H^{\pm}$, in addition to the lighter CP-even $h$ which can be identified as the Higgs boson discovered at the LHC with the mass of $m_h \approx 125$ GeV. Flavour changing neutral currents whose existence is experimentally severely constrained can be avoided at the tree level by imposing the softly-broken $Z_2$ symmetry.

Yukawa interactions of additional Higgs bosons to the SM fermion are given as

$$- \mathcal{L}_{Yukawa} = \sum_{f=u,d,\ell} \left[ \frac{m_f}{v} \bar{\xi}_f \bar{f} f h + \frac{m_f}{v} \bar{\xi}_f \bar{f} f H - \frac{i m_f}{v} \bar{\xi}_f \bar{f} f A \gamma_5 A \right]$$

$$+ \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} \xi_A u_L + m_d \xi_A d_L \right\} d_R H^+ + \frac{\sqrt{2} m_{\ell}}{v} \xi_A \bar{\ell} \gamma_5 \ell R H^+ + \text{H.c.} \right\}, \quad (1)$$

* The talk is based on Ref. [1] in collaboration with S. Kanemura and Y.J. Zheng.
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where the scaling factor $\xi_f^\phi$ with $\phi = h, H, A$ and $f = u, d, \ell$ is a function of the mixing angles, $\alpha$ and $\beta$, in the mass matrix of the CP-even and odd components of the Higgs doublets, respectively. In the 2HDM with the softly-broken $Z_2$ symmetry, there are four kinds of the model for the Yukawa interactions, depending on the assignment of the fermion parity under the $Z_2$ symmetry, namely, Type-I, Type-II, Type-X and Type-Y. Detail expressions for the scaling factors in each type of Yukawa interactions can be found, e.g., in Ref. [4]. For any type of Yukawa interactions, couplings of the additional Higgs boson to top quarks are enhanced for small $\tan\beta$. Thus, the signatures for such parameter regions can be heavy Higgs bosons which dominantly decay into top quarks. Therefore, the searches for the multi-top-quarks events can be a new signals of additional Higgs bosons in future collider experiments.

III. MULTI-TOP QUARKS PRODUCTION AT THE LHC

First, we study multi-top-quarks production at the LHC through the production of additional Higgs boson(s). The process with largest cross section is expected to be

$$pp \rightarrow t \bar{t} H(t \bar{t} A) \rightarrow t \bar{t} t \bar{t},$$

(2)

since it occurs via the strong interaction.

The other process can be pair production of $H$ and $A$,

$$pp \rightarrow H A \rightarrow t \bar{t} t \bar{t},$$

(3)

followed by the decays of $H$ and $A$ into top quarks, and also the associated production of $H^\pm$ and $H(A)$, which subsequently decay into $t \bar{b}(\bar{t}b)$ and $t \bar{t}$

$$pp \rightarrow H^\pm H(A^\pm A) \rightarrow t \bar{b}(\bar{t}b)/t \bar{t} t \bar{t},$$

(4)

resulting three top-quarks plus one bottom-quark final-states.

The hadronic cross sections for the above processes can be predicted in perturbative QCD, and by multiplying the branching ratios of additional Higgs bosons into top quarks, expected number of events can be estimated [1]. The cross sections of the production of a pair of additional Higgs bosons, [2] and [4], do not depend on $\tan\beta$, but that of the process [2] does through the top Yukawa coupling. The largest cross sections are realized for the mass of additional Higgs bosons at around 350 GeV. Below this value, the branching ratio into $t \bar{t}$ is suppressed because one of the top quarks is forced to be off-shell, while above that value the production cross sections of additional Higgs bosons decrease. For $\tan\beta = 1$, the cross section of the four top-quarks production can be at most 6 fb (50 fb) for the LHC 8 TeV (14 TeV).

The CMS Collaboration has set the limit on the cross section at 8 TeV as $\sigma_{4t}(8\text{ TeV}) < 32\text{ fb}$ at the 95% CL (confidence level) [2], by observing the lepton plus multi-jets events. On the other hand, the SM prediction to the four top-quarks production at the LHC 8 TeV is about 1 fb. Therefore, the limit is not enough to constrain the parameter regions in the 2HDM.

We study the prospect of measuring four top-quarks production by the production of additional Higgs bosons at the LHC with the collision energy of 14 TeV in the 2HDM. The total cross section within the SM is estimated to be $\sigma_{SM} = 15\text{ fb}$ with $\delta\sigma_{SM} = 4\text{ fb}$ [2]. We follow the signal-to-background analysis in Ref. [3]. In their analysis, the background rate of $B = 7.2\text{ fb}$ is obtained with the signal efficiency of $\epsilon = 0.03$. By taking into account the statistical and systematical uncertainties for the signal, SM and background processes, the accuracy of measuring the signal cross section $\sigma_S$ can be estimated to be

$$\frac{\delta\sigma_S}{\sigma_S} = \sqrt{\frac{(\sigma_S + \delta\sigma_{SM})\epsilon + B}{\sigma_S^2\epsilon^2L} + \frac{\delta\sigma_{SM}^2\epsilon^2 + (\delta B)^2}{\sigma_S^2\epsilon^2}},$$

(5)

where $\delta B$ denotes the systematic uncertainty of the background rate which is taken to be $\delta B = 0.05B$ in our analysis. By solving Eq. (5), we find that the signal total cross section $\sigma_S$ greater than 25 fb (63 fb) is required to achieve $\delta\sigma_S/\sigma_S < 0.5$ (0.2) with the integrated luminosity of $L = 300\text{ fb}^{-1}$. In our setup, the total uncertainty is dominated by the systematic uncertainty from the background.

In Fig. 1 we show the parameter regions in which the additional Higgs bosons contribution can be detected in the four top-quarks events at the 2$\sigma$ and 5$\sigma$ CL in the Type-II and Type-X 2HDM. The dependence on the type of Yukawa interactions is small. We find that only $\tan\beta \lesssim 1.5$ regions can be probed at the 2$\sigma$ CL at most. Since these regions are constrained by flavor experiments, the LHC searches in the four top-quarks events may not have significant impact on exploring the parameter regions in the 2HDMs.
which is allowed even in the case with designed detector performance at the ILC experiment [2].

Clustering, flavor tagging, detector acceptance and momentum resolution effects, etc [1]. We make use of the such as $H_t$, the decay branching ratio of $\beta$.

To extract the signal events out of the SM background, we impose following selection cuts; (i) small thrust,

$$T < 0.25$$

in this work, we propose an inclusive analysis which take into account all the channels at once for simplicity.

Jets plus missing channels. In principle, optimal selection cuts may be constructed for each channel. However,
Alternatively, the single production process can be increased by the

$$m_{H,A} \lesssim 500 \text{ GeV.}$$

where no $H \rightarrow WW, ZZ, hh$ or $A \rightarrow Zh$ decay is induced. If we take $\sin(\beta - \alpha) = 0.99$, these decay modes become non-zero, and even

FIG. 1: Contour plot for the discovery reach of the four top-quarks events at the LHC with 3000 fb$^{-1}$ data in the 2HDM Type-II and Type-X. Discovery regions at the 2$\sigma$ [5$\sigma$] CL are shown in the dashed [solid] lines.

IV. MULTI-TOP QUARKS PRODUCTION AT THE ILC

Second, we consider the multi-top-quarks production at the ILC. In the 2HDM, the four top-quarks final-state is generated via the pair production of $H$ and $A$,

$$e^+e^- \rightarrow HA,$$

which is kinematically accessible for $\sqrt{s} \geq m_H + m_A$, and via the single production of $H$ or $A$ [8],

$$e^+e^- \rightarrow t\bar{t}H(t\bar{t}A),$$

which is allowed even in the case with $\sqrt{s} \leq m_H + m_A$. The $HA$ pair production cross section does not depend on $\tan \beta$ at the tree level, and thus the four top-quarks production rate depends on $\tan \beta$ only through the decay branching ratio of $H$ and $A$. On the other hand, the single production process can be increased by the enhanced Yukawa coupling of $H$ and $A$ to top quarks [2].

We perform a simulation analysis on four top-quarks production at the ILC. The SM backgrounds processes, such as $e^+e^- \rightarrow t\bar{t}$, $t\bar{t}b\bar{b}$, $t\bar{t}l^+l^-$ are taken into account. The SM four top-quarks production cross section is negligibly small. Our simulation analysis includes the decay of top quarks, QCD showering, hadronization, jet clustering, flavor tagging, detector acceptance and momentum resolution effects, etc [1]. We make use of the designed detector performance at the ILC experiment [2].

Through the decay of top quarks, the four top-quarks events can be observed in all-hadronic, single lepton plus jets plus missing momentum, dilepton plus jets plus missing, trilepton plus jets plus missing, tetralepton plus jets plus missing channels. In principle, optimal selection cuts may be constructed for each channel. However, in this work, we propose an inclusive analysis which take into account all the channels at once for simplicity. To extract the signal events out of the SM background, we impose following selection cuts; (i) small thrust, $T < 0.77$, (ii) $N_{bj} \geq 3$, and (iii) large multiplicity of hard objects, $N_T = 2N_{lep} + N_{jet} \geq 10$, where $N_{lep}$ is the sum of the number of isolated leptons ($e$ and $\mu$) and the number of hadronic $\tau$-jets, $N_{bj}$ ($N_j$) is a number of $b$-tagged (light-flavor) jets in a event.

The event distributions of the signal and background processes in the kinematical variables used for the selection cuts as well as the background reduction and signal detection efficiencies can be found in Ref. [1]. We obtain that the signal events can be extracted with the detection efficiency of 40-50% depending on the mass of additional Higgs bosons, while only about 50 ab of the background events is remained. The accessible value of the total cross section is evaluated to be 0.034-0.048 fb (0.11-0.15 fb) at the $2\sigma$ (5$\sigma$) CL, depending on the mass of additional Higgs bosons.

We evaluate the parameter regions in the 2HDMs where the four top-quarks events can be detected at the ILC 1 TeV run with the integrated luminosity of 1 ab$^{-1}$. We take into account the statistical uncertainties only, since the systematical ones can be expected to be well under control at lepton colliders. In Fig. 2 we plot the solid-line (dashed-line) contours in the $(m_{H,A}, \tan \beta)$ plane where the four top-quarks events can be detected at the $2\sigma$ (5$\sigma$) CL at the ILC 1 TeV with $L = 1$ ab$^{-1}$. Results for Type-I (left) and Type-II (right) 2HDMs are shown for example. For Type-II, $\tan \beta$ up to about 7 (6) can be probed at the $2\sigma$ (5$\sigma$) CL for $m_{H,A} \lesssim 500$ GeV. For Type-I, the events can be detected for any value of $\tan \beta$, as long as $m_{H,A} \lesssim 500$ GeV.

The result for Type-I strongly depends on our choice of taking $\sin(\beta - \alpha) = 1$ where no $H \rightarrow WW, ZZ, hh$ or $A \rightarrow Zh$ decay is induced. If we take $\sin(\beta - \alpha) = 0.99$, these decay modes become non-zero, and even
dominant for larger $\tan \beta$. In this case, the four top-quarks events can be observed up to about $\tan \beta \simeq 8$ (5) at the $2\sigma$ (5$\sigma$) CL. The discovery reaches for $\sin(\beta - \alpha) = 0.99$ are also shown in blue lines in Fig. 2.

The searches for multi-top-quarks events at the LHC and the ILC explore the different parameter regions in the 2HDM. At the LHC Run-II and 3000 fb$^{-1}$, only the parameter regions with $\tan \beta \lesssim 1.5$ can be surveyed. On the other hand, at the ILC 1 TeV, we find that the parameter regions with larger $\tan \beta$ can be surveyed as long as $m_{H,A} \lesssim 500$ GeV. For Type-II, the parameter regions with $\tan \beta \simeq 7$ can be explored. For Type-I, because the decay mode into a top-quark pair is dominant for any value of $\tan \beta$, the detection of the four top-quarks events is anticipated in any value of $\tan \beta$. This result is modified to $\tan \beta \lesssim 9$ in the case of $\sin(\beta - \alpha) = 0.99$.

V. SUMMARY

We have studied the direct searches of the additional Higgs bosons in multi-top-quarks events at the LHC and the ILC. As a benchmark model of the extended Higgs sector, we have considered the two Higgs doublet models with softly-broken discrete symmetry. At the LHC, the systematical uncertainties of estimating the SM backgrounds dominate the uncertainty, and therefore, the searches can only survey the parameter regions with $\tan \beta \lesssim 1.5$ which is disfavored by experimental constraints. At the ILC, we have shown that the parameter regions with $\tan \beta \lesssim 8-15$ can be surveyed, depending on the type of Yukawa interactions, although the mass reach is almost limited by the collision energy. The direct searches for the multi-top-quark events at the LHC and the ILC can be complementary to explore the wider parameter regions in the 2HDMs.

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[1] S. Kanemura, H. Yokoya and Y. J. Zheng, [arXiv:1505.01089 [hep-ph]].
[2] T. Behnke (ed.) et al., [arXiv:1306.6329 [physics.ins-det]].
[3] S. Kanemura, H. Yokoya and Y. J. Zheng, Nucl. Phys. B 886 (2014) 524.
[4] M. Aoki, S. Kanemura, K. Tsumura and K. Yagyu, Phys. Rev. D 80 (2009) 015017.
[5] V. Khachatryan et al. [CMS Collaboration], JHEP 1411 (2014) 154.
[6] G. Bevilacqua and M. Worek, JHEP 1207 (2012) 111.
[7] B. Lillie, J. Shu and T. M. P. Tait, JHEP 0804 (2008) 087.
[8] S. Kiyoura, S. Kanemura, K. Odagiri, Y. Okada, E. Senaha, S. Yamashita and Y. Yasui, [hep-ph/0301172].
[9] S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, Phys. Rev. D 90 (2014) 075001.