Loop induced singlet scalar production through the vector like top quark at future lepton colliders

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Abstract

In this paper, we explore the signature of a simplified model which includes a new singlet scalar state and a vector like quark at future lepton colliders. In particular, we study the production of the new singlet scalar in association with a photon, which proceeds through loop level diagrams involving vector like top quark partner, at future $e^{-}e^{+}$ colliders with different center-of-mass energies from 500 GeV to 3 TeV. To show the sensitivity of the process, the exclusion limits on the parameter space of the model are presented considering the decay of the singlet scalar into a pair of Higgs boson, followed by the decay of Higgs bosons into $b\bar{b}$ pairs. The results are compared to those obtained from the electroweak precision data and the ones which could be achieved from the single scalar production channel at a future lepton collider.
1 Introduction

With the Higgs boson discovery at Run I of the LHC \cite{1,2}, followed by measurements of its properties from the LHC second run \cite{3-6}, the spontaneous symmetry breaking mechanism of the Standard Model (SM) is confirmed. However, there are still unanswered questions in the SM framework which motivates proposing theoretical models beyond the SM. Among them, there are models with extended scalar and fermion sectors of the SM, which are well motivated to control the instability of electroweak vacuum \cite{7-9} and hierarchy problem \cite{10,11}. In particular, models of extended quark sector with vector like quarks (VLQs) appear in composite Higgs models \cite{12,13}, extra dimensions \cite{14}, little Higgs models \cite{15}, gauging of the flavor group \cite{16}, and non-minimal supersymmetric SM \cite{17}. In this work, the concentration is on a simplified model with minimal fields content and interactions, which adds a singlet scalar and a vector like top quark to the SM. In the considered scenario, both the new scalar and vector like top quark mix with the Higgs boson and top quark, respectively \cite{9,18}.

In the SM context, based on the next-to-next-to-leading calculation, the Higgs boson self coupling $\lambda$ tends to be negative at a high energy scale of around $10^{10}$ GeV which causes instability of the Higgs vacuum. The vacuum stability is quite dependent on how precise the top quark mass is measured. It is notable that the current measured values of the Higgs boson and top quark masses suggest that the vacuum could be metastable \cite{19-23}. In the considered simplified model, the presence of the new scalar can have a positive contribution to the Higgs boson quartic coupling $\lambda$ and consequently could push the Higgs boson potential toward the stable phase. It is worth mentioning that the added VLQ in this minimal model will help preserve the perturbativity of the new scalar quartic coupling \cite{9}.

There are tight bounds on the couplings of the light quarks to the heavy vector like quarks from flavor physics \cite{24}, as a result in this simplified model no interaction among the vector like quark and the first two quark generations is considered. The new scalar state couples to the massive SM particles through its mixing with Higgs boson and couples to the massless photon and gluon via loops involving the VLQ and top quark \cite{9,18,25-32}.

So far, no evidence for existing such new particles have been observed by the collider experiments. There are studies for vector like top quark $T$ at the LHC by the ATLAS and CMS experiments, where the searches have been performed for vector like top quark pair $T\bar{T}$ production through strong interactions \cite{33-35}. In these searches, the $T$ and $\bar{T}$ quarks are assumed to decay into $tZ$, $tH$, and $Wb$ and the searches have been performed in different channels like single lepton, multilepton, and full hadronic. In all studied final states, the results are compatible with the SM expectations hence limits have been set on the model parameters. Other studies on constraining the masses, couplings of the vector like top quark $T$, and the new scalar can be found in Refs. \cite{18,36,42}. Model-independent approach using effective operators for the vector like top quark partner has been studied in Ref. \cite{43}. The vector like top quark $T$ can also be produced singly in association with a light quark and either a top quark or a bottom quark at the LHC which has been the subject of several studies such as Refs. \cite{44,45}.

In addition to the direct searches, the parameter space of the simplified model with a singlet scalar and VLQ has been probed using the electroweak precision observables as well as the Higgs coupling precision measurements that could be found in Ref. \cite{9}. The requirement of vacuum stability and the unitarity of the VLQ and scalar scatterings constrain the parameter space. Among all the limits, those from vacuum stability are the tightest \cite{9}.

In addition to the theoretical motivations for the existence of heavy states of VLQs and a singlet scalar state, there are observed excesses in the di-Higgs production at the LHC in the $b\bar{b}\gamma\gamma$ and $4b$ final states on the invariant masses around 300 GeV \cite{46} and 280 GeV \cite{47}, respectively. If
persists, such excesses have no explanation in the SM context and one could consider new model beyond the SM to explain them.

The future electron-positron colliders such as International Linear Collider (ILC) [48, 49], Compact Linear Collider (CLIC) with a possibility of going to high center-of-mass energy up to 3 TeV [50], the Future Circular Collider FCC-ee [51, 52], and Circular Electron-Positron Collider CEPC [53] provide very clean places to measure the SM parameters and to search for new physics effects. Lack of hadronic initial state, low amount of background, and accurate knowledge of initial beam energy would flatten the way of precision studies or discovery of new particles.

The goal of the present work is to study the phenomenology of the direct production of the singlet scalar at the future lepton colliders and inquire its effects on the phenomenology of lepton colliders. In particular, the production of the singlet scalar in association with a photon is studied because the final state has an energetic photon and could be used as a handle to reduce the background contributions and trigger the signal events. The process proceeds through loop level diagrams where the VLQ contributes to the loops, therefore the channel is sensitive to the related parameters of the VLQ and would be a complementary process to the other channels to search for the model. This paper is organized as the following: In section 2, a brief review of the model and its main properties are given. Section 3 provides a phenomenological study on the new scalar associated with a photon at the high energy lepton colliders. In section 4, the possible final states and potential bounds on the model parameters are presented. The results are compared with the constraints obtained from the LHC data and from the expectation of the single scalar production channel at a future high energy lepton collider. Section 5 is devoted to the summary and conclusions.

2 The model

In this section, a brief description of the simplified model where the SM is extended by adding a new neutral singlet scalar $S$ and a vector like quark $T$ is given. The VLQ $T$ carries the same quantum numbers as the right-handed top quark and mixes only with the SM top quark. More detailed description of the model could be found in Refs. [9, 18]. In the new scenario, the scalar, Yukawa and gauge sectors of the SM Lagrangian receive changes:

$$\mathcal{L} \supset \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{gauge}},$$

where

$$\mathcal{L}_{\text{scalar}} = \frac{1}{2} (D_\mu H) (D^\mu H) + \frac{1}{2} \partial_\mu S \partial^\mu S - \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$+ \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4,$$

here $H$ is the SM Higgs boson doublet and the new scalar field is denoted by $S$. To keep the Yukawa term $ST^T$, no $Z_2$ symmetry is applied however conventionally $a_1, b_1, b_3$ are set to zero. With such assumptions on the couplings, one can explain all the relevant measurements and also explain the motivations for which the model has been proposed. Both the SM Higgs doublet and new scalar $S$ acquire non-zero vacuum expectation values:

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_H + h + i\phi^0) \\ i\phi^+ \end{pmatrix}, \quad S = (s + v_S),$$

2
where $v_H$ is the vacuum expectation value (vev) of the SM Higgs boson and is $\approx 246$ GeV and the vev of the singlet scalar is denoted by $v_S$. After the spontaneous symmetry breaking and expanding the Lagrangian around its minimum, the squared mass matrix has the following form:

$$M_{\text{scalar}}^2 = \begin{pmatrix} 2\lambda v_H^2 & a_2 v_H v_S \\ a_2 v_H v_S & 2b_4 v_S^2 \end{pmatrix},$$

(4)

and the squared masses of the physical eigenstates are found to be:

$$m_{h_1,h_2}^2 = \lambda v_H^2 + b_4 v_S^2 \mp \sqrt{(b_4 v_S^2 - \lambda v_H^2)^2 + a_2^2 v_H^2 v_S^2}.$$  

(5)

The physical eigenstates $h_{1,2}$ are related to the singlet scalar field $s$ and the SM Higgs field $h$ through the following transformation:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix},$$

(6)

where $\theta$ is the mixing angle and is defined as:

$$\tan(2\theta) = \frac{a_2 v_H v_S}{b_4 v_S^2 - \lambda v_H^2}.$$  

(7)

It is assumed that the $h_1$ scalar field is the SM Higgs boson with a mass of $m_{h_1} = 125$ GeV, which will denoted as $h$ after here. To have the vacuum stability at large energy scales, the mixing angle $\theta$ has to be small [54, 55]. Considering the LHC measurements of the Higgs boson, electroweak precision data, and respecting the vacuum stability conditions impose that $|\sin(\theta)| \lesssim 0.2$.

The third quark generation Yukawa part of the Lagrangian is modified as follows:

$$\mathcal{L}_{\text{Yukawa}} = y_t S^\text{int} \bar{t}_L^\text{int} T_R^\text{int} + y_t Q^\text{int} \bar{t}_L^\text{int} H_T^\text{int} + y_t Q^\text{int} Q^\text{int} b_R + \lambda T^\text{int} \bar{Q}_{L RT}^\text{int} H_T^\text{int} ,$$

where int index stands for weak interaction eigenstates, $\bar{Q}_L$ is left-handed third generation quark doublet, $\bar{Q}_L = (\bar{t}_L^\text{int} \bar{b}_L^\text{int})$ and $H = i\sigma_2 H^*$. We note that one could add a Dirac mass term for vector like top quark $T$ to the above Lagrangian however after the spontaneous symmetry breaking $T$ acquires mass. Therefore, in order to reduce the number of free parameters in the model, Dirac mass term is not added to the Lagrangian. A term proportional to $T_R^\text{int} t_L^\text{int}$ can also be present in the $\mathcal{L}_{\text{Yukawa}}$, however, it can be removed by a redefinition of the right-handed fields $(t_R^\text{int}, T_R^\text{int})$ [56].

After the spontaneous symmetry breaking, the SM top quark $t_L^\text{int}$ and vector like top quark $T_R^\text{int}$ mix and the mass matrix can be written as:

$$\mathcal{M}_{\text{Yukawa}} = \begin{pmatrix} y_t v_H / \sqrt{2} & \lambda_T v_H / \sqrt{2} \\ 0 & y_T v_S \end{pmatrix}.$$  

(8)

The mass matrix is diagonalized by the unitary transformation with $\theta_L$ and $\theta_R$ rotation angles:

$$\begin{pmatrix} t_{L/R} \\ T_{L/R} \end{pmatrix} = U_{L/R} \begin{pmatrix} t_{L/R}^\text{int} \\ T_{L/R}^\text{int} \end{pmatrix},$$

(9)

where $t_{L/R}$ and $T_{L/R}$ are the physical mass eigenstates and the unitary matrices are written as:

$$U_{L/R} = \begin{pmatrix} \cos \theta_{L/R} & -\sin \theta_{L/R} \\ \sin \theta_{L/R} & \cos \theta_{L/R} \end{pmatrix}.$$  

(10)
The squared mass eigenvalues for the SM top quark and the vector like quark $T$ are found to be:

$$m_{T,t}^2 = \frac{1}{4} \left( y_t^2 v_H^2 + \lambda_T^2 v_H^2 + 2y_t^2 v_S^2 \pm \sqrt{(y_t^2 v_H^2 + \lambda_T^2 v_H^2 + 2y_t^2 v_S^2)^2 - 8y_t^2 v_H^2 y_t^2 v_S^2} \right) ,$$  

where the lighter eigenstate is assumed to be the SM top quark with $m_t = 173.2$ GeV and the heavier is taken as the vector like $T$ with a mass $m_T$. Two mixing angles are related through the following relation \[57\]:

$$\tan(\theta_R) = \frac{m_t}{m_T} \tan(\theta_L) .$$  

It is clear that the left-handed mixing angle is always dominant, in particular for the heavy vector like $T$. The Yukawa coupling terms, mass terms of the $t, T$ and the mixing term between $t$ and $T$ are given by:

$$\mathcal{L}_{\text{Yukawa}} \ni \frac{m_T}{v_H v_S} \left( s_L^2 v_S (h - i\phi^0) + c_L^2 v_H s \right) \bar{T}_L T_R$$

$$+ \frac{m_t}{v_H v_S} \left( c_L^2 v_S (h - i\phi^0) + s_L^2 v_H s \right) \bar{t}_L t_R$$

$$+ \frac{m_T}{v_H v_S} s_{LCL} (v_S (h - i\phi^0) - v_H s) \bar{t}_L T_R$$

$$+ \frac{m_t}{v_H v_S} s_{LCL} (v_S (h - i\phi^0) - v_H s) \bar{T}_L t_R,$$

where $s_L(c_L) \equiv \sin\theta_L (\cos\theta_L)$. Electroweak gauge interactions of vector like quark $T$ with the quantum number $Q_T = 2/3$ and $Y_T = 4/3$ with the SM third quark generation $t, b$ are as follows:

$$\mathcal{L}_{\text{gauge}} \ni \bar{i} \partial \theta + i b \bar{b} b + i \bar{T} \partial T$$

$$+ e (Q_t \bar{t} \gamma^\mu t + Q_T \bar{T} \gamma^\mu T + Q_b \bar{b} \gamma^\mu b) A_\mu$$

$$+ \frac{g}{\sqrt{2}} \left( (c_L \bar{t} \gamma^\mu P_L b + s_L \bar{T} \gamma^\mu P_L \bar{T}) W^+ + (c_L \bar{b} \gamma^\mu P_L t + s_L \bar{b} \gamma^\mu P_L T) W^- \right)$$

$$+ \frac{g}{c_w} \left( T \gamma_\mu \left( \frac{s_w^2}{2} P_L - Q_T s_w^2 \right) T + \bar{t} \gamma_\mu \left( \frac{c_w^2}{2} P_L - Q_t s_w^2 \right) t \right.$$ 

$$+ \bar{b} \gamma_\mu \left( -\frac{1}{2} P_L - Q_b s_w^2 \right) b + i \bar{t} \gamma_\mu \frac{s_{LCL}}{2} P_L T + \bar{T} \gamma_\mu \frac{s_{LCL}}{2} P_L T \right) Z_\mu ,$$

where $\theta_w$ is Weinberg weak mixing angle, $s_w(c_w) \equiv \sin\theta_w (\cos\theta_w)$ and $P_L = (1 - \gamma_5)/2$ is projection operator. More explanation for driving of the above interactions are given in appendix of Ref. \[18\].

The simplified model followed here has five unknown parameters which consists of the mass of vector like top quark $m_T$, the new singlet scalar mass $m_{h_2}$, vacuum expectation value of the singlet scalar $v_S$, and the mixing angles $\theta_L$ and $\theta$ in the fermion and scalar sectors, respectively.

In Ref. \[58\], the production of a new scalar singlet $h_2$ has been studied via vector boson fusion ($e^- + e^+ \rightarrow h_2 + \nu \bar{\nu}$) at a high energy lepton collider with the center-of-mass energy of 3 TeV. In particular, it has been found that a future high energy lepton collider would be able to examine the single scalar production rate with a few tens of atto-barn. The production of the scalar $h_2$ associated with a $Z$ boson at a lepton collider operating at the center-of-mass energy of 240 GeV has been studied in Ref. \[59\]. In section 3, we calculate the production cross section of the scalar $h_2$ in association with a photon at the lepton colliders. The cross section is presented at different center-of-mass energies of the electron-positron collisions and its dependence on the free parameters of the model is presented.
3 Singlet scalar production in association with a photon

In this section, we propose an alternative way to have access to parameter space of the simplified model by considering the process $e^-e^+ \rightarrow h_2\gamma$ which proceeds via loops with contributions from SM fermions, gauge bosons and, the VLQ. In Ref. [60], the cross section of the associated production of a photon and a Higgs boson in the context of Minimal Supersymmetric Standard Model (MSSM) has been calculated. The production rates for the associated production of both the CP-even and CP-odd Higgs bosons of the MSSM have been studied. For the CP-even MSSM Higgs boson production with a photon, other s-channel Feynman diagrams involving loops with charginos, charged Higgs bosons, squarks, and sleptons appear and in the t-channel box diagrams chargino/sneutrino and neutralino/selectron contribute to the production process. The production rate of the Higgs boson in association with a photon at electron-positron colliders, in the context of extended Higgs models, like the two-Higgs-doublet model, the inert doublet model, and the inert triplet model (ITM) has been studied in Ref. [61]. The authors found that the charged scalars of these models via loop diagrams can generate sizable contributions to the production cross section of $h + \gamma$. The potential of the LHC to probe the new physics effects in the SMEFT (SM Effective Field Theory) framework through the Higgs boson production associated with a photon has been studied in Ref. [62]. The next-to-leading order QCD corrections to the production of a Higgs boson associated with a photon has been calculated in Ref. [63], where it has been shown that these corrections could increase the production rate up to 20%.

Within the simplified model, the $e^-e^+ \rightarrow h_2\gamma$ process proceeds through loop-level Feynman diagrams which include SM fermions and gauge bosons as well as the additional contributions from the vector like top quark. Representative Feynman diagrams contributing to the process $e^-e^+ \rightarrow h_2\gamma$ are presented in Fig.1. There are s-channel diagrams with $Z/\gamma$ boson exchange in which virtual $W$ boson, heavy SM fermion (mostly top and bottom quarks) as well as the vector like top quark in the loops are involved. The new singlet scalar $h_2$ couples to the top quark via both the fermion and scalar mixing which causes triangle diagrams in the s-channel production. The t-channel Feynman diagrams involve $W,Z,\nu_e$ and electron exchanges. Contributions from s-channel diagrams with the SM Higgs boson $h$ and its interference with the $Z$ boson or photon is negligible.

Since the process occurs at higher order electroweak interaction, the cross section is expected
to be rather small, however the signal is very clean specially due to the presence of an energetic photon in the final state. This would allow to achieve a reasonable background suppression and leads to have a good sensitivity in particular using the expected large amount of data by the future lepton colliders.

Within the considered simplified model in this work, the one-loop amplitude, neglecting the mass of electron, for the $h_2 + \gamma$ production can be written as the sum of the amplitudes of all contributing diagrams:

$$
\mathcal{M} = \sum_{k=1,2} \sum_{\nu=+, -} \Lambda_k^\pm C_k^\pm,
$$

(15)

where $\Lambda_k^\pm$ have the following form [60]:

$$
\Lambda_1^\pm = T(q_+)(1 \pm \gamma_5)(\ell^* \cdot p_\gamma q_+ - \hat{p}_\gamma \epsilon_\gamma q_+^*) u(q_-)
$$

$$
\Lambda_2^\pm = T(q_+)(1 \pm \gamma_5)(\ell^* \cdot p_\gamma q_+ - \hat{p}_\gamma \epsilon_\gamma q_+^*) u(q_-),
$$

(16)

where $q_{\pm}$ are the momenta of the $e^\pm$ beams, $p_\gamma$ is the four-momentum of external photon and $\epsilon_\gamma$ is the corresponding polarization vector and $C_k^\pm$ represent form factor coefficients obtained by summing the diagrams depicted in Fig.1:

$$
C_k^\pm = C_k^{\gamma, \pm} + C_k^{Z, \pm} + C_k^{W, \text{box}} + C_k^{Z, \text{box}},
$$

(17)

where $C_k^{\gamma, \pm}$ and $C_k^{Z, \pm}$ represent the contributions of $\gamma$ and $Z$ propagators in s-channel diagrams for vertex corrections and $C_k^{W, \text{box}}$ and $C_k^{Z, \text{box}}$ are the contributions of box diagrams. The total cross section for unpolarized beam is obtained as:

$$
\frac{d\sigma}{d \cos \theta_s} = \frac{s - m_{h_2}^2}{64\pi s} \frac{1}{(16\pi^2)^2} \left[ u^2 (|C_1^+|^2 + |C_1^-|^2) + t^2 (|C_2^+|^2 + |C_2^-|^2) \right],
$$

(18)

where $\theta_s$ is the the angle between the incoming electron and outgoing photon. To obtain the above differential cross section, an averaging over the helicities of the incoming leptons and a sum over the outgoing photon polarization has been performed. $s, t$ and $u$ are the Mandelstam variables and are defined as $s = (q_- + q_+)^2$, $t = (q_+ - p_\gamma)^2$ and $u = (q_+ - p_\gamma)^2$. The $C_k^\pm$ coefficients can be written as a function of Passarino-Veltman functions. The $C_k^{\gamma, \pm}$ coefficient contains contribution from three diagrams involving $W$ boson, top quark and vector like top quark in the loop-induced vertex $h_2\gamma\gamma$ and the $C_k^{Z, \pm}$ includes $W$ boson, top quark and vector like top quark contribution in loop-induced vertex $h_2Z\gamma$. $C_k^{\gamma, \pm}$ and $C_k^{Z, \pm}$ have the following forms:

$$
C_1^{\gamma, \pm} = C_2^{\gamma, \pm} = -\frac{e}{2} \frac{1}{s} G^\gamma,
$$

$$
C_1^{Z, \pm} = C_2^{Z, \pm} = -\frac{e z^\pm}{4s_w c_w} \frac{1}{s - M_Z^2} G^Z,
$$

(19)

where $e$ is the size of electron electric charge, $z^+ = -1 + 2s_w^2$, and $z^- = 2s_w^2$. Considering both the bosonic and fermionic contributions in s-channel vertex correction, $G^\gamma$ and $G^Z$ are obtained
as follows:

\[
G^\gamma = \frac{e^3 M_W}{s_w} \left[ F_{\gamma,W} s_\theta - \sum_f 4 Q_f^2 N_c \frac{m_f^2}{M_W^2} F_f^\gamma s_\theta \right. \\
- 4 F^f \frac{m_f^2}{M_W^2} N_c Q_f^2 \left( r s_\theta^2 c_\theta + c_\theta^2 s_\theta \right) - 4 F^T \frac{m_T^2}{M_W^2} N_c Q_T^2 \left( r c_\theta^2 c_\theta + s_\theta^2 s_\theta \right) \left. \right],
\]

\[
G^Z = \frac{e^3 M_W}{c_w s_w} \left[ F_{Z,W} s_\theta + \sum_f 2 Q_f N_c \frac{m_f^2}{M_W^2} (I_f^3 - 2 s_w^2 Q_f) F_f^\gamma s_\theta \right. \\
+ 2 Q_T N_c \frac{m_T^2}{M_W^2} (I_T^2 s_L^2 - 2 s_w^2 Q_T) (s_\theta^2 s_\theta + r c_\theta^2 c_\theta) F^T \\
+ 2 Q_i N_c \frac{m_i + m_T}{M_W^2} \frac{s_L^2 c_L^2 (s_\theta - r c_\theta)}{F_i} \\
+ 2 Q_T N_c \frac{m_i + m_T}{M_W^2} \frac{s_L^2 c_L^2 (s_\theta - r c_\theta)}{F_i^T} \right],
\]

(20)

where \( m_f, Q_f \) and \( I_f^3 \) are the mass, electric charge and third component of weak isospin of the fermion \( f \) (\( f \) can be all fermions except for \( t \) and \( T \)), respectively. \( N_c \) is the number of QCD colors and \( r \equiv v_H/v_S \) and \( s_\theta \) (\( c_\theta \) \( \equiv \sin \theta \) (\( \cos \theta \)). Functions \( F \) with various indices in Eq.20 are the combination of Passarino-Veltman scalar functions and are given in the Appendix. In order to ensure all the contributing Feynman diagrams from SM and new physics are consistently included, the gauge invariance of the matrix elements is checked through validating the Ward-Takahashi identity. In the model, the new scalar couples to the SM particles through mixing with the Higgs boson as \( h = c_\theta h_1 + s_\theta h_2 \). Therefore, the new scalar coupling to weak gauge bosons and fermions (except the top quark) are similar to the SM Higgs coupling and just receive a correction factor \( s_\theta \). The scalar coupling to top quark is modified by both mixing scalar and Yukawa top sectors (see Eq.13). Among the diagrams, the amplitude of box diagrams \( (C_{k}^{\pm W,Z box}) \) have the same form as the SM Higgs associated production with photon by only replacing \( m_H \to m_{h_2} \) and adding \( s_\theta \) which comes from \( VV h_2 \) coupling. The explicit forms of \( C_{k}^{\pm W,Z box} \) as a function of Passarino-Veltman scalar functions are given in Appendix.\[A\] While in triangle diagrams, vertices \( \gamma h_2 \) and \( Z \gamma h_2 \) are modified due to the contribution of singlet scalar couplings to top quark, \( W \) boson, and the vector like top quark partner. Comparing the box and triangle diagrams contributions, we find the box diagram contributions are expected to be suppressed significantly at small scalar mixing angle. Package-X \[64\] and LoopTools \[65\] are used to reduce the tensor integrals and to evaluate the one loop Feynman integrals. The Passarino-Veltman formalism according to Ref. \[60\] is employed in this work.

The differential cross section \( d\sigma(e^- e^+ \to h_2 \gamma)/d \cos \theta_s \) for three center-of-mass energies \( \sqrt{s} = 500 \text{ GeV} \) and \( 1.3 \text{ TeV} \) are presented in Fig.2. The distributions are shown for two values of \( s_\theta = \pm 0.15 \) which are denoted by solid (\(+0.15\)) and dotted (\(-0.15\)) curves. We see that the cross section is not symmetric on \( s_\theta \) which was expected as the cross section \( e^- e^+ \to h_2 \gamma \) is proportional to \( (A s_\theta + B c_\theta)^2 \). Obviously, the cross section is considerably sensitive to the sign of \( s_\theta \) and larger cross section is expected for the negative values of \( s_\theta \) in particular for the low center-of-mass energies of 500 GeV and 1 TeV. Moreover, the effect of the sign of \( s_\theta \) is negligible
at small scattering angles at $\sqrt{s} = 3\,\text{TeV}$. One can also see that the angular distribution for both signs of $s_\theta$ is symmetric on the scattering angle and no forward-backward asymmetry is expected.

![Graph](image)

**Figure 2:** Differential cross section of $h_2 + \gamma$ production as a function of scattering angle $\cos\theta_s$ for $m_{h_2} = 280\,\text{GeV}$ for different center-of-mass energies with $s_\theta = 0.15$ (solid) and $s_\theta = -0.15$ (dotted).

In Fig.3, the total cross section of $e^-e^+ \rightarrow h_2 \gamma$ is presented as a function of center-of-mass energy $\sqrt{s}$ for $m_{h_2} = 280\,\text{GeV}$, $s_L = 0.15$, and $s_\theta = \pm0.15$. The cross sections are shown for two scenarios of assumption on the two sets of free parameters: $(m_T, v_S) = (1000, 350), (750, 400)\,\text{GeV}$. For both scenarios, the maximum value of cross section occurs at $\sqrt{s} \sim 2m_T$. As can be seen, the cross section increases rapidly up to $T\bar{T}$ threshold then drops slightly with increasing the center-of-mass energy like $1/s$. It is notable that the contribution of s-channel diagrams to the total cross section is dominant with respect to the box and t-channel diagrams. The impact of the sign of $s_\theta$ is explicit in particular for the center-of-mass energies less than $T\bar{T}$ threshold, i.e. $2m_T$. While as the center-of-mass energy increases, the effect of the sign of $s_\theta$ is hardly distinguishable. In addition, the cross section enhances when $m_T$ goes up.

![Graph](image)

**Figure 3:** Total cross section of $h_2 + \gamma$ production as a function of center-of-mass energy $\sqrt{s}$ for different values of $m_T$ and $v_S$ with $s_\theta = 0.15$ (solid) and $s_\theta = -0.15$ (dotted).
Figure 4: Total cross section of $h_2 + \gamma$ production as a function of vector like top quark mass, $m_T$, for different values of center-of-mass energies with $s_\theta = 0.15$ (solid) and $s_\theta = -0.15$ (dotted).

To illustrate the dependence of the cross section of $e^- e^+ \rightarrow h_2 \gamma$ process on the mass of vector like top quark, we show the cross section as a function of $m_T$ in Fig.4. The cross section are shown for three center-of-mass energies of 500 GeV, 1 TeV, and 3 TeV for two cases of the sign of mixing angle of $s_\theta = \pm 0.15$. The plot shows that the cross section increases quickly with $m_T$ up to $\sim m_T = \sqrt{s}/2$ then it remains almost constant. The cross section is larger for the larger center-of-mass energy. Fig.5 shows the cross section in terms of the mass of new scalar $m_{h_2}$ for $\sqrt{s} = 500$ GeV, 1 and 3 TeV. Because of the larger phase space, the production cross section is large for the low mass of scalar and it decreases by increasing $m_{h_2}$. Therefore, more sensitivity is expected to the regions in parameter space with a light scalar. We also note that the cross section decreases more rapidly for the center-of-mass energies of 500 GeV and 1 TeV than the 3 TeV case.

Figure 5: The total cross section of $h_2 + \gamma$ production as a function of scalar mass $m_{h_2}$ for three center-of-mass energies with $m_T = v_S = 500$ GeV (left) and $m_T = 1$ TeV, $v_S = 350$ GeV (right) and for $s_\theta = 0.15$ (solid) and $s_\theta = -0.15$ (dotted).
4 Experimental signatures and possible constraints

There are various direct searches for the new scalar $h_2$ at the hadron and lepton colliders. Of particular interest in this work is to perform the search for $h_2$ via its production in association with a photon at the future lepton colliders.

Based on the decay modes of $h_2$, different topologies are expected to be produced. The $h_2$ decay mechanism is almost similar to the Higgs boson, dominated by the $b\bar{b}$ pair and two gluons in low mass region while the decay channels $WW, ZZ, t\bar{t}$, and $hh$ are dominant at large mass region. For more illustration, the branching fractions of the $h_2$ decays into the SM particles are shown in Fig.6 for $v_S = 500$ GeV and $s_\theta = s_L = 0.15$. With increasing $m_{h_2}$, decay modes of $WW, ZZ$, and $hh$ are dominant with respect to $t\bar{t}$. From Fig.6 one can see that at $m_{h_2} \geq 200$ GeV, decay channels $h_2 \rightarrow gg/\gamma\gamma/f\bar{f}$, where $f$ denotes all fermion except top quark, are negligible.

As mentioned before, the scalar $h_2$ in the models containing a new scalar and VLQs could account for excesses observed in di-Higgs events reported by ATLAS collaboration at $m_{h_2} = 280$ GeV or 300 GeV [46,47]. In these models the mass of VLQ is constrained to $m_{VLQ} \gtrsim 800$ GeV where $m_{VLQ}$ can be either top quark or bottom quark partner. Moreover, the experimental constraints from the recent LHC data, Higgs and precision electroweak data have been obtained for $h_2$ and VLQ in Refs. [18,66]. In this section, we derive potential bounds on the free parameters of the simplified model in $e^-e^+\rightarrow h_2+\gamma$ final state and compare them with the ones obtained from Higgs and precision electroweak data measured at the LHC [18]. Given the interested mass range of $h_2$, some of the appropriate, dominant, and clean decay modes are listed in Table 1 as a reference for discussion of the experimental signatures.

In order to make an estimation of the potential of $e^-e^+ \rightarrow h_2 + \gamma$ process to probe the parameter space of the model, we consider the $h_2$ decay into $hh$, followed by $h \rightarrow b\bar{b}$, i.e. $e^-e^+ \rightarrow h_2 \gamma \rightarrow hh\gamma \rightarrow b\bar{b}b\bar{b}\gamma$. These choices are made due to the large branching fractions of $h_2 \rightarrow hh$ and $h \rightarrow b\bar{b}$. The cross section of signal including the whole decay chain is computed as $\sigma(e^-e^+ \rightarrow h_2\gamma) \times Br(h_2 \rightarrow hh) \times Br(h \rightarrow b\bar{b})^2$. For $m_h = 125$ GeV, the Higgs boson branching ratio decaying into $b\bar{b}$ is 0.584 [67]. The main background processes to this final state are:

$$e^+e^- \rightarrow 4b + \gamma,$$

$$e^+e^- \rightarrow 2b + 2j + \gamma \ (j = u,d,s,c,g), \text{ two jets (j) are misidentified as b-jets},$$

$$e^+e^- \rightarrow 4j + \gamma \ (j = u,d,s,c,g), \text{ four jets (j) are misidentified as b-jets},$$

(21)
Table 1: The $h_2$ to $WW$, $hh$, $ZZ$, and $t\bar{t}$ decay channels as well as the branching fractions of some of the decay modes.

| ZZ mode | $[Br\%]$ | tt mode | $[Br\%]$ | WW mode | $[Br\%]$ | hh mode | $[Br\%]$ |
|---------|-----------|---------|-----------|---------|-----------|---------|-----------|
| $(ll')$(ll') | $[1\%]$ | $(l\nu b)(q\bar{q} b)$ | $[44\%]$ | $(l\nu l')(q\bar{q} l')$ | $[44\%]$ | $(b\bar{b})(b\bar{b})$ | $[34\%]$ |
| $(ll)(qq)$ | $[14\%]$ | $(l\nu b)(l\nu b)$ | $[10\%]$ | $(l\nu l')(l\nu l')$ | $[10\%]$ | $(b\bar{b})(ll)$ | $[7\%]$ |
| $(ll)(l\nu l')(l\nu l')$ | $[4\%]$ | $(q\bar{q} b)(q\bar{q} b)$ | $[46\%]$ | $(q\bar{q} q')(q\bar{q} q')$ | $[46\%]$ | $(ll)(ll)$ | $[0.4\%]$ |
| $(qq)(q'q')$ | $[49\%]$ | | | | | $(b\bar{b})(\gamma\gamma)$ | $[0.3\%]$ |
| $(qq)(\nu\nu)$ | $[28\%]$ | | | | | $(ll)(\gamma\gamma)$ | $[0.03\%]$ |
| $(\nu\bar{\nu})(\nu\bar{\nu})$ | $[4\%]$ | | | | | $(WW)(WW)$ | $[5\%]$ |

where all processes with off-shell $\gamma$, $Z$, $W^\pm$, and gluons are included.

The background rates are computed using MadGraph5-AMC@NLO package [68]. The efficiency of $b$-tagging for a jet originating from the hadronization of a bottom quark is taken 70%, and misidentification rates of 10% and 1.5% are assumed for charm quark and light-flavor jets [69].

To select signal and background events and achieve a good sensitivity, the following requirements are applied: energy ($E$) and pseudorapidity ($\eta = -\ln \tan(\frac{\theta}{2})$) of b-jets are required to be larger than 20 GeV and $|\eta_{b\text{-jet}}| < 2.5$, respectively. Since the photon is expected to carry a large amount of energy due to its recoil against the heavy scalar $h_2$, its energy is required to be greater than 300 GeV and $|\eta_{\gamma}| < 2.5$. The signal and background efficiencies after these cuts are found to be 20.02% and 0.67%, respectively. As in the signal events, the $b\bar{b}$ pairs come from the Higgs boson decays, it is required $100 \text{ GeV} \leq m_{b\bar{b}} \leq 150 \text{ GeV}$. This requirement has a strong power to suppress the background processes where the final state jets are not originating from Higgs bosons decays. For instance, it provides a rejection rate at the order of $10^{-5}$ for the major background processes, i.e. $e^- + e^+ \rightarrow 4b + \gamma$.

It should be mentioned that there are background processes in which an additional jet is misidentified as a photon. Such a signature may occur when neutral pions with large boost appear from jet fragmentation and decay to two photons. The showers from two photons can overlap in the electromagnetic calorimeter (ECAL) and will be observed as a single photon. The probability for a jet to be misidentified as a photon is dependent on the photon energy and is of the order of $10^{-5-4}$ [70] for an energetic fake photon. Therefore, requiring a photon with $E \geq 300 \text{ GeV}$ suppresses the fake background contribution to a negligible level. A realistic detector simulation is necessary to estimate the fake background contribution.

In Fig. 7 the 95% CL excluded regions for $v_H/v_S$ versus $s_\theta$ and $v_H/v_S$ versus $m_t/m_T$ for the center-of-mass energy of 3 TeV with an integrated luminosity of $3 \text{ ab}^{-1}$ are presented. The excluded regions are depicted for two scenarios of background contributions: scenario I where no uncertainty is considered on the number of expected background and scenario II where an uncertainty of 50% is taken on the number of expected backgrounds. The dot-dashed red curves in Figs. 7 show the contours of favoured region at 95% CL extracted from the precision electroweak data and Higgs boson measurements at the LHC [18]. As it can be seen, with the proposed selection in this work, for any value of the sine of mixing angle $s_\theta \in [0.05, 0.2]$, any value of $v_H/v_S$ above 0.6, corresponding to $v_H \gtrsim 410 \text{ GeV}$, can be excluded. This would be a considerable improvement with respect to current bounds from electroweak precision tests and LHC Higgs data. The 95% CL excluded region for $v_H/v_S$ versus $m_t/m_T$ indicates that a part of allowed region from electroweak precision tests and Higgs data corresponding to large mass of VLQ is accessible via the $h_2\gamma$ channel. For example, any value of $v_S \lesssim 0.82 \text{ TeV}$ can be excluded for $m_T = 1.4 \text{ TeV}$.

In Fig. 8 the excluded regions of the parameter space in the plane of $(s_\theta^2, m_{h_2})$ at 95% CL are
shown. The results are presented for two scenarios of the expected background and are compared with those derived from 36 fb$^{-1}$ of LHC data at 13 TeV, $\nu^−\nu^+ \to h_2 + \nu\bar{\nu}$ process [58] at CLIC, and the high luminosity LHC (HL-LHC) [58]. As it can be seen, using the $\nu^−\nu^+ \to h_2 + \nu\bar{\nu}$ process at the center-of-mass energy of 3 TeV with an integrated luminosity of 3 ab$^{-1}$, any value of $s_0^2$ above $\sim 0.0015$ for $m_{h_2} \sim 300$ GeV could be excluded. The HL-LHC would be able to exclude $s_0^2 \gtrsim 0.005$ for $m_{h_2} \sim 300$ GeV using the scalar decay into di-boson [58]. The associated production of $h_2$ with a photon is sensitive to the low mass region for the allowed values of $s_0^2$ from the present constraints, i.e. $s_0^2 \lesssim 0.1$. Considering no uncertainty would provide access to a mass region of $m_{h_2} \lesssim 700$ GeV and taking into account an uncertainty of 50% on the expected background would reduce the sensitivity to mass, with almost 200 GeV. As we can see, the $h_2\gamma$ process would be able to scan a remarkable region of $s_0^2 \lesssim 0.004$ with $m_{h_2} \lesssim 500$ GeV where the HL-LHC is not sensitive to. From Fig. [8], we also see that the excluded region derived from $h_2\gamma$ plays a complementary role to single scalar production at CLIC [58]. In particular, the $h_2\gamma$ process could probe the model at low mass region, i.e. $m_{h_2} \lesssim 500$ GeV, with $s_0^2 \lesssim 0.001$ which is not accessible by the single scalar production.

The presented results here are at the center-of-mass energy of 3 TeV and are based on an integrated luminosity of 3 ab$^{-1}$ which is expected to be attainable by CLIC according to Ref. [71]. However, it should be noted that different center-of-mass energies are sensitive to a particular part of the model parameters. For example, as the left plot of Fig.[5] shows, the total cross section of $h_2\gamma$ process is maximum at $\sqrt{s} = 1$ TeV for $m_T = v_S = 500$ GeV while with $m_T = 1$ TeV, $v_S = 350$ GeV, collisions at $\sqrt{s} = 3$ TeV provides the largest cross section. Therefore, performing the study at different center-of-mass energies and combination would allow to extend the sensitivity to larger part of the parameter space.

In this investigation, we only concentrated on di-Higgs decay mode of $h_2$, followed by $h \to b\bar{b}$, and cuts on few kinematic variables are considered to reduce the backgrounds. However, there are rooms for improving the sensitivity which could be achieved by (i) considering other decay modes of the Higgs boson as mentioned in the last column of Table [4] (ii) using the other decay
Figure 8: The green areas are the 95% CL excluded regions of the parameter space in the plane of ($s_\theta^2, m_{h_2}$) with no (left) and with 50% (right) uncertainty on the expected number of background events. These regions are derived from $e^-e^+\rightarrow h\gamma$ with subsequent $h_2$ decay into di-Higgs and Higgs decays into $b\bar{b}$. The results are shown under assumption of $m_T=1$ TeV, $s_L=0.15$ and $v_S=350$ GeV. The red and orange shaded regions obtained from LHC direct search with the scalar decays into di-boson and from indirect searches. The constraints from CLIC at $\sqrt{s}=1.5$ TeV and $1.5$ ab$^{-1}$ (dot-dashed blue) and $\sqrt{s}=3$ TeV and $3$ ab$^{-1}$, obtained from the single scalar channel, are depicted with blue and purple curves. The constraints from the HL-LHC with a luminosity of $300$ fb$^{-1}$ (yellow) and $3$ ab$^{-1}$ (dashed gray) are presented for comparison as well [58].

channels of $h_2$ like $h_2 \rightarrow WW, ZZ, t\bar{t}$ and combination of all channels together; (iii) using various kinematic variables to suppress the contributions and also exploiting sophisticated methods such as multivariate techniques to distinguish signal events from background events once a MC event generator for signal is available.

5 Summary

To summarize, we performed an analytic calculation for the production cross section of a neutral singlet scalar heavier than the observed SM Higgs boson in association with a photon ($h_2\gamma$) in the context of a simplified SM extension model, at a lepton collider. In this model the scalar mixes with the SM Higgs boson and can couple to a pair of SM massless bosons, i.e. photon and gluon, at loop level via a vector like fermion which mixes with the top quark. Such a model provides the possibility to stabilize the electroweak vacuum [9] and can explain the enhancement observed in di-Higgs mass spectrum by the ATLAS collaboration [46,47].

We presented the size of the $h_2\gamma$ cross section for various center-of-mass energies which would be reached at future lepton colliders. The cross section is calculated in terms of the model parameters and in general it was found to be small but the signal signatures are rather clean and could be used to span the parameter space of the model. To examine the potential of the process to explore the model, we concentrated on the decay of $h_2$ to $hh$ followed by the Higgs bosons decays into $b\bar{b}$ pairs. Using a set of selection cuts for the signal events which efficiently suppress the background contributions, the exclusion regions at 95% CL are derived. This was done as an example at the center-of-mass energy of $\sqrt{s}=3$ TeV with an integrated luminosity of $3$ ab$^{-1}$. Overall, the results indicate that the associated production of the scalar $h_2$ with a photon is sensitive to a part of the parameter space at low scalar mass and low values of the
mixing angle which is out of access at the HL-LHC. A comparison of the results with the single scalar production at CLIC suggests that the $h_2\gamma$ process has the ability to complement the single scalar channel at very low values of the mixing angle.

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A Appendix

The $F$ functions appeared in Eq.20 are defined as:

$$F^a = 4 \left[ C_{22}^a + C_{12}^a + C_2^a + \frac{C_0^a}{4} \right],$$
$$F^n = 2 (m_t + m_T) (C_{22}^n + C_{12}^n) + m_T C_0^n + (m_t + 3 m_T) C_2^n - (m_t - m_T) C_1^n,$$
$$F^l = F^n [m_t \leftrightarrow m_T, n \rightarrow l],$$

(22)

where $a = f, t, T$ and $C_{ij}$s are the common scalar two and three point Passarino-Veltman functions which are defined as:

$$C_{ij}^f \equiv C_{ij}(s, 0, m_{h_2}^2, m_f^2, m_f^2, m_f^2),$$
$$C_{ij}^t \equiv C_{ij}(s, 0, m_{h_2}^2, m_t^2, m_t^2, m_t^2),$$
$$C_{ij}^T \equiv C_{ij}(s, 0, m_{h_2}^2, m_T^2, m_T^2, m_T^2),$$
$$C_{ij}^n \equiv C_{ij}(s, 0, m_{h_2}^2, m_T^2, m_T^2, m_T^2),$$
$$C_{ij}^l \equiv C_{ij}(s, 0, m_{h_2}^2, m_T^2, m_T^2, m_T^2).$$

(23)

In Eq.20 $F^{\gamma/Z,W}$ are the combination of Passarino-Veltman scalar functions:

$$F^{\gamma,W} = 4 \left( \frac{m_{h_2}^2}{M_W^2} + 6 \right) (C_{12} + C_{22} + C_2) + 16 C_0,$$
$$F^{Z,W} = 2 \left[ \frac{m_{h_2}^2}{M_W^2} (1 - 2 c_w^2) + 2 (1 - 6 c_w^2) \right] (C_{22} + C_{12} + C_2) + 4 (1 - 4 c_w^2) C_0,$$

(24)

with

$$C_{ij} \equiv C_{ij}(s, 0, m_{h_2}^2, M_W^2, M_W^2, M_W^2).$$

(25)

The $C_{1,2}^{\pm Wbox}$ and $C_{1,2}^{\pm Zbox}$ in Eq.17 have the following forms:
\[ C^{+}_{1,Wbox} = -\frac{e^4 M_W s_\theta}{s_w^3} \left[ D^a_1 + D^b_1 + D^b_{13} - D^a_{13} - D^a_{33} \right], \]
\[ C^{+}_{2,Wbox} = -\frac{e^4 M_W s_\theta}{s_w^3} \left[ D^a_2 + D^a_{23} + D^b_2 - D^b_{23} - D^b_{33} \right], \]
\[ C^{-}_{1,2,Wbox} = 0, \]
\[ C^{\pm}_{1,Zbox} = -\frac{2 e^4 M_W s_\theta g_e^{\pm 2}}{s_w c_w^2} \left[ D^c_{13} + D^c_{33} \right], \]
\[ C^{\pm}_{2,Zbox} = \frac{2 e^4 M_W s_\theta g_e^{\pm 2}}{s_w c_w^2} \left[ D^b_5 + D^b_{12} + D^b_{23} \right], \] (26)

where \( g_e^- \equiv I_e^3 / (s_w c_w) - Q_e s_w / c_w \), and \( g_e^+ \equiv -Q_e s_w / c_w \). Four point Passarino-Veltman functions \( D_{ij} \) are defined as follows:

\[ D^a_{ij} \equiv D_{ij}(0, s, m_{h_2}^2, u, 0, 0, 0, M^2_W, M^2_W, M^2_W), \]
\[ D^b_{ij} \equiv D_{ij}(0, s, 0, t, 0, m_{h_2}^2, 0, M^2_W, M^2_W, M^2_W), \]
\[ D^c_{ij} \equiv D_{ij}(0, u, m_{h_2}^2, t, 0, 0, 0, M^2_Z, M^2_Z, M^2_Z). \] (27)

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