Abstract

The double Higgs production in the models with isospin-triplet scalars is studied. It is shown that in the see-saw type II model the mode with an intermediate heavy scalar, $pp \rightarrow H + X \rightarrow 2h + X$, may have the cross section which is compatible with that in the Standard Model. In the Georgi-Machacek model this cross section could be much larger than in SM since the vacuum expectation value of the triplet can be large.
This paper is our present to Valery Anatolievich Rubakov on his anniversary. Many students (and not only students) in the world are studying Physics reading his excellent books, papers and listening his brilliant lectures.

I. INTRODUCTION

After the discovery of the Higgs-BE boson at LHC \[1\] the next steps to check the Standard Model (SM) are: the measurement of the coupling constants of the Higgs boson with other SM particles ($t\bar{t}, WW, ZZ, b\bar{b}, \tau\bar{\tau}, \ldots$) with better accuracy and the measurement of the Higgs self-coupling which determines the shape of the Higgs potential. In the SM the triple and quartic Higgs couplings are predicted in terms of the known Higgs mass and vacuum expectation value. Deviations from these predictions would mean the existence of New Physics in the Higgs potential. The triple Higgs coupling can be measured at LHC in double Higgs production, in which the gluon fusion dominates: $gg \rightarrow hh$. However, the $2h$ production cross section is very small. According to \[2\] at $\sqrt{s} = 14$ TeV the cross section $\sigma^{NLO}(gg \rightarrow hh) = 40.2$ fb with $(10 - 15)\%$ accuracy. For the final states with the reasonable signal/background ratios (such as $hh \rightarrow b\bar{b}\gamma\gamma$) only at HL-LHC with integrated luminosity $\int Ldt = 3000$ fb$^{-1}$ double Higgs production will be found and triple Higgs coupling will be measured \[3\]. We are looking for the extensions of the SM Higgs sector in which the double Higgs production is enhanced.

One of the well-motivated examples of non-minimal Higgs sector is provided by the seesaw type II mechanism of the neutrino mass generation \[6\]. In this mechanism a scalar isotriplet with hypercharge $Y_\Delta = 2 (\Delta^{++}, \Delta^+, \Delta^0)$ is added to the SM. The vacuum expectation value (vev) of the neutral component $v_\Delta$ generates Majorana masses of the left-handed neutrinos. There are two neutral scalar bosons in the model: the light one in which the doublet Higgs component dominates and which should be identified with the particle discovered at LHC ($h; M_h = 125$ GeV), and the heavy one in which the triplet Higgs component dominates ($H$). The neutrino masses equal $f_i v_\Delta$, where $f_i$ ($i = 1, 2, 3$) originates from Yukawa couplings of Higgs triplet with the lepton doublets. If neutrinos are light due to a small value of $v_\Delta$ while $f_i$ are of the order of one, then $H$ decays into the neutrino pairs. Three

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1 The decays into $b\bar{b}\tau\bar{\tau}$ and $b\bar{b}W^+W^-$ final states can be even more promising for the measurement of triple Higgs coupling \[4\],[5].
states $H^{\pm\pm}$ (or $\Delta^{\pm\pm}$), $H^{\pm}$, and $H$ are almost degenerate in the model considered in Sect. II and the absence of the same-sign dileptons at LHC from $H^{\pm\pm} \rightarrow l^\pm l^\pm$ decays provides the lower bound $m_H > 400$ GeV [7]. We are interested in the opposite case: $v_\Delta$ reaches the maximum allowed value while neutrinos are light because of small values of $f_i$. In this case $H \rightarrow hh$ can be the dominant decay mode of a heavy neutral Higgs. In this way we get an additional mechanism of the double $h$ production at LHC.

The bound $m_{H^{\pm\pm}} > 400$ GeV [7] cannot be applied now since $H^{\pm\pm}$ mainly decays into the same-sign diboson [8]. We only need $H$ to be heavy enough for $H \rightarrow hh$ decay to occur. This case is analyzed in Sect. II. The invariant mass of additionally produced $hh$ state peak at $(p_1 + p_2)^2 = m_H^2$ which is a distinctive feature of the proposed mechanism, see also [9, 10].

$H$ contains a small admixture of the isodoublet state which makes gluon fusion a dominant mechanism of $H$ production at LHC. The admixture of the isodoublet component in $H$ equals approximately $2v_\Delta/v$, where $v \approx 250$ GeV is the vacuum expectation value of the neutral component of isodoublet, and in Sect. II for $\sqrt{s} = 14$ TeV and $M_H = 300$ GeV we will get $\sigma (gg \rightarrow H) \approx 25$ fb. Taking into account that $\text{Br} (H \rightarrow hh)$ is about 80%, we obtain 50% enhancement of double Higgs production in comparison with SM.

Since the nonzero value of $v_\Delta$ violates the well checked equality of the strength of charged and neutral currents at tree level,

$$\frac{g^2/M_W^2}{\bar{g}^2/M_Z^2} = 1 + 2\frac{v_\Delta^2}{v^2},$$

$v_\Delta$ should be less than 5 GeV (see Sect. II). The numerical estimate of $gg \rightarrow H$ cross section was made for maximum allowed value $v_\Delta = 5$ GeV when the isodoublet admixture is about 5%.

The bound $v_\Delta < 5$ GeV is removed in the Georgi-Machacek model [9], in which in addition to $\Delta$ a scalar isotriplet with $Y = 0$ is introduced. If the vev of the neutral component of this additional field equals $v_\Delta$ then we get just one in the r.h.s. of (1): correction proportional to $v_\Delta^2$ is cancelled. Thus $v_\Delta$ can be much larger than 5 GeV. The bounds on $v_\Delta$ come from the measurement of the 125 GeV Higgs boson couplings to vector bosons and fermions, which would deviate from their SM values: $c_i \rightarrow c_i \left[1 + a_i (v_\Delta/v)^2\right]$.

The consideration of an enhancement of $2h$ production in GM variant of see-saw type II model is presented in Sect. II. Since at the moment the accuracy of the measurement of $c_i$ values in $h$ production and decay is poor, $v_\Delta$ as large as 50 GeV is allowed and
\( \sigma (gg \to H) \) can reach 2 pb value which makes it accessible with the integrated luminosity \( \int L \, dt = 300 \text{ fb}^{-1} \) prior to HL-LHC run. We summarize our results in Conclusions.

II. DOUBLE \( h \) PRODUCTION IN \( H \) DECAYS AT LHC

A. Scalar sector of the see-saw type II model

In this subsection we will present the necessary formulas; for a detailed description see \cite{[12]}. In addition to the SM isodoublet field \( \Phi \),

\[
\Phi \equiv \begin{bmatrix} \Phi^+ \\ \Phi^0 \end{bmatrix} \equiv \begin{bmatrix} \frac{1}{\sqrt{2}} (v + \varphi + i\chi) \end{bmatrix},
\]

in see-saw type II an isotriplet is introduced:

\[
\Delta \equiv \frac{\Delta \tilde{\sigma}}{\sqrt{2}} = \begin{bmatrix} \Delta^3/\sqrt{2} & (\Delta^1 - i\Delta^2)/\sqrt{2} \\ (\Delta^1 + i\Delta^2)/\sqrt{2} & -\Delta^3/\sqrt{2} \end{bmatrix} \equiv \begin{bmatrix} \delta^+ / \sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+ / \sqrt{2} \end{bmatrix},
\]

\[
\delta^0 = \frac{1}{\sqrt{2}} (v_\Delta + \delta + i\eta).
\]

Here \( \tilde{\sigma} \) are the Pauli matrices.

The scalar sector kinetic terms are

\[
\mathcal{L}_{\text{kinetic}} = |D_\mu \Phi|^2 + \text{Tr} \left[ (D_\mu \Delta)^\dagger (D_\mu \Delta) \right],
\]

where

\[
D_\mu \Phi = \partial_\mu \Phi - \frac{g}{2} A_\mu^a \sigma^a \Phi - \frac{g'}{2} B_\mu \Phi,
\]

\[
D_\mu \Delta = \left[ \partial_\mu \Delta^a + g\varepsilon^{abc} A_\mu^b \Delta^c - ig' B_\mu \Delta^a \right] \frac{\sigma^a}{\sqrt{2}} = \partial_\mu \Delta - ig \frac{A_\mu^a \sigma^a}{\sqrt{2}} - ig' B_\mu \Delta.
\]

Hypercharge \( Y_\Phi = 1 \) was substituted for isodoublet and \( Y_\Delta = 2 \) for isotriplet. The terms quadratic in vector boson fields are the following:

\[
\mathcal{L}_{V^2} = g^2 |\delta^0|^2 W^+ W^- + \frac{1}{2} g^2 |\Phi^0|^2 W^+ W^- + \bar{g}^2 |\delta^0|^2 Z^2 + \frac{1}{4} g^2 |\Phi^0|^2 Z^2.
\]

Vector boson masses are

\[
\begin{align*}
M_W^2 &= \frac{g^2}{4} (v^2 + 2v_\Delta), \\
M_Z^2 &= \frac{\bar{g}^2}{4} (v^2 + 4v_\Delta).
\end{align*}
\]
For the ratio of vector boson masses neglecting the radiative corrections from isotriplet (not a bad approximation as far as the heavy triplet decouples) we get:

\[
\frac{M_W}{M_Z} \approx \left( \frac{M_W}{M_Z} \right)_{\text{SM}} \left( 1 - \frac{v^2}{v^2} \right). \tag{9}
\]

Comparing the result of SM fit [14, p.145], \( M_{W}^{\text{SM}} = 80.381 \text{ GeV} \), with the experimental value, \( M_{W}^{\text{exp}} = 80.385(15) \text{ GeV} \), at 3\( \sigma \) level we get the following upper bound:

\[
v_\Delta < 5 \text{ GeV}, \tag{10}
\]

and since the cross sections we are interested in are proportional to \( (v_\Delta)^2 \) we will use an upper bound \( v_\Delta = 5 \text{ GeV} \) for numerical estimates in this section.

From the numerical value of Fermi coupling constant in muon decay we obtain:

\[
v^2 + 2v_\Delta^2 = (246 \text{ GeV})^2, \tag{11}\]

so for \( v_\Delta \lesssim 5 \text{ GeV} \) the value \( v = 246 \text{ GeV} \) can be safely used in deriving \( v_\Delta \).

The scalar potential looks like:

\[
V(\Phi, \Delta) = -\frac{1}{2} m_\Phi^2 (\Phi^\dagger \Phi) + \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 + M_\Delta^2 \text{Tr} [\Delta^\dagger \Delta] + \frac{\mu}{\sqrt{2}} (\Phi^T i \sigma^2 \Delta^\dagger \Phi + h.c.), \tag{12}
\]

which is a truncated version of the most general renormalizable potential (see for example [13], eq. (2.6)). We may simply suppose that the coupling constants which multiply the omitted terms in the potential (\( \lambda_1, \lambda_2, \lambda_4, \) and \( \lambda_5 \)) are small. In the case of SM only the first line in \( (12) \) remains; mass of the Higgs boson equals \( m_\Phi = 125 \text{ GeV} \) while its expectation value \( v^2 \approx m_\Phi^2 / \lambda \approx (246 \text{ GeV})^2, \lambda \approx 0.25. \)

Since at the minimum of \( (12) \) the following equations are valid:

\[
\begin{cases}
\frac{1}{2} m_\Phi^2 = \frac{1}{2} \lambda v^2 - \mu v_\Delta, \\
M_\Delta^2 = \frac{1}{2} \mu v_\Delta^2, 
\end{cases} \tag{13}
\]

for vev’s of isodoublet and isotriplet we obtain:

\[
v^2 = \frac{m_\Phi^2 M_\Delta^2}{\lambda M_\Delta^2 - \mu^2}, \tag{14}
\]

\[
v_\Delta = \frac{\mu m_\Phi^2}{2 \lambda M_\Delta^2 - 2 \mu^2} = \frac{\mu}{2} \frac{v^2}{M_\Delta^2}. \tag{15}
\]
Quadratic in $\varphi$, $\delta$ terms according to (12) are

$$V(\varphi, \delta) = \frac{1}{2} m_\Phi^2 \varphi^2 + \frac{1}{2} M_\Delta^2 \delta^2 - \mu v \varphi \delta.$$ (16)

Here and below the terms suppressed as $(v_\Delta/v)^2$ are omitted.

Denoting the states with the definite masses as $h$ and $H$ we obtain:

$$
\begin{bmatrix}
\varphi \\
\delta
\end{bmatrix} =
\begin{bmatrix}
\cos \alpha & -\sin \alpha \\
\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
h \\
H
\end{bmatrix},
\tan 2\alpha = \frac{2\mu v}{M_\Delta^2 - m_\Phi^2},
$$ (17)

$$M_h^2 = \frac{1}{2} \left( m_\Phi^2 + M_\Delta^2 - \sqrt{(M_\Delta^2 - m_\Phi^2)^2 + 4\mu^2 v^2} \right) \approx m_\Phi^2,$$ (18)

$$M_H^2 = \frac{1}{2} \left( m_\Phi^2 + M_\Delta^2 + \sqrt{(M_\Delta^2 - m_\Phi^2)^2 + 4\mu^2 v^2} \right) \approx M_\Delta^2.$$(19)

Since $\tan 2\alpha \approx 4v_\Delta/v \ll 1$, mass eigenstate $h$ consists mostly of $\varphi$ and $H$ consists mostly of $\delta$. We suppose that the particle observed by ATLAS and CMS is $h$, so $M_h$ is about 125 GeV.

The scalar sector of the model in addition to the massless goldstone bosons, which are eaten up by the vector gauge bosons, contains one double charged field $H^{++}$, one single charged field $H^+$, and three real neutral fields $A$, $H$, and $h$. $H^+$ is mostly $\delta^+$ with small $\Phi^+$ admixture, $A$ is mostly $\eta$ with small $\chi$ admixture. All these particles except $h$ are heavy; their masses equal $M_\Delta$ with small corrections proportional to $v_\Delta^2/M_\Delta$.

**B. $H$ decays**

The second and fourth terms in potential (12) contribute to $H \rightarrow 2h$ decays:

$$\frac{\lambda}{2} (\Phi^\dagger \Phi)^2 \rightarrow \frac{\lambda v}{2} \varphi^3,$$ (20)

$$\frac{\mu}{\sqrt{2}} (\Phi^T i \sigma^2 \Delta^\dagger \Phi + h.c.) \rightarrow -\frac{\mu}{2} \delta (\varphi^2 - \chi^2),$$ (21)

where in the second line $\chi$ is dominantly a goldstone state which forms the longitudinal $Z$ polarization.

With the help of (17) we obtain the expression for the effective lagrangian which describes $H \rightarrow 2h$ decay:

$$\mathcal{L}_{Hhh} = \frac{\mu}{2} \left[ 1 + \frac{3}{\left( \frac{M_H}{M_h} \right)^2 - 1} \right] H h^2 = v_\Delta M_H^2 \left[ 1 + \frac{3}{\left( \frac{M_H}{M_h} \right)^2 - 1} \right] H h^2.$$(22)
In the see-saw type II model neutrino masses are generated by the Yukawa couplings of isotriplet $\Delta$ with lepton doublets. These couplings generate $H \rightarrow \nu\nu$ decays as well. As it was noted in [8] for $v_\Delta > 10^{-3}$ GeV diboson decays dominate. It happens because the amplitude of diboson decay is proportional to $v_\Delta$, while Yukawa couplings $f_i$ are inversely proportional to it, $f \sim m_\nu/v_\Delta$. That is why for $v_\Delta \gtrsim 1$ GeV leptonic decays are completely negligible.

The amplitudes of $H \rightarrow ZZ$ and $H \rightarrow W^+W^-$ decays are contained in [7]:

$$\mathcal{L}_{HVV} = g^2 \left( v_\Delta \cos \alpha - \frac{1}{2} v \sin \alpha \right) W^+W^+H + \tilde{g}^2 \left( v_\Delta \cos \alpha - \frac{1}{4} v \sin \alpha \right) Z^2H$$

$$\approx -g^2 \frac{M_h^2/M_H^2}{1 - M_h^2/M_H^2} v_\Delta W^+W^+H + \tilde{g}^2 \frac{1 - 2M_h^2/M_H^2}{1 - M_h^2/M_H^2} v_\Delta Z^2H,$$

and we see that $H \rightarrow W^+W^-$ decay is suppressed (see, for example, [15]).

$H \rightarrow t\bar{t}$ decay occur through $\varphi$ admixture:

$$\mathcal{L}_{Htt} = \sin \alpha \frac{m_t}{v} t\bar{t}H = \frac{2v_\Delta/v}{1 - M_h^2/M_H^2} \frac{m_t}{v} t\bar{t}H,$$

as well as $H$ decay into two gluons:

$$\mathcal{L}_{Hgg} = \frac{\alpha_s}{12\pi} \sin \alpha G^2_{\mu\nu}.$$

Let us note that all the amplitudes of $H$ decays are proportional to triplet vev $v_\Delta$.

For the decay probabilities we obtain:

$$\Gamma_{H \rightarrow hh} = \frac{v_\Delta^2 M_H^3}{v^4} \frac{1 + 2 \left( \frac{M_h}{M_H} \right)^2}{8\pi} \left[ 1 - \left( \frac{M_h}{M_H} \right)^2 \right]^{-2} \sqrt{1 - 4\frac{M_h^2}{M_H^2}},$$

$$\Gamma_{H \rightarrow ZZ} = \frac{v_\Delta^2 M_H^3}{v^4} \frac{1 - 2 \left( \frac{M_h}{M_H} \right)^2}{8\pi} \left[ 1 - \left( \frac{M_h}{M_H} \right)^2 \right]^{-2} \left( 1 - 4\frac{M_h^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4} \right) \sqrt{1 - 4\frac{M_Z^2}{M_H^2}},$$

$$\Gamma_{H \rightarrow WW} = \frac{v_\Delta^2 M_H^3}{v^4} \frac{M_{W/2}}{4\pi} \left[ 1 - \left( \frac{M_h}{M_H} \right)^2 \right]^{-2} \left( 1 - 4\frac{M_W^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4} \right) \sqrt{1 - 4\frac{M_W^2}{M_H^2}},$$

$$\Gamma_{H \rightarrow t\bar{t}} = \frac{v_\Delta^2 N_c m_t^2 M_H}{2\pi} \frac{1}{(1 - M_h^2/M_H^2)^2} \left( 1 - 4\frac{m_t^2}{M_H^2} \right)^{3/2},$$

where $N_c = 3$ is the number of colors. Finally for the width of decay into two gluon jets we obtain:

$$\Gamma_{H \rightarrow gg} = \frac{v_\Delta^2 M_H^3}{v^4} \frac{1}{2\pi} \left( \frac{\alpha_s}{3\pi} \right)^2 \left( 1 - \frac{M_h^2}{M_H^2} \right)^{-2},$$
TABLE I. The cross sections of Higgs production via $gg$ fusion. Values for the SM Higgs are taken from Table 4 in [16]. All numbers in this and following tables correspond to 14 TeV LHC energy.

| $M_h$ (GeV) | 125 | 300 |
|-------------|-----|-----|
| $\sigma_{gg\to h}$ (pb) | $49.97 \pm 10\%$ | $11.07 \pm 10\%$ |
| $M_H$ (GeV) | X | 300 |
| $\sigma_{gg\to H}$ (fb) | X | $25 \pm 10\%$ |

and it is always negligible.

In what follows we suppose that $M_H < 350$ GeV and the decay $H \to t\bar{t}$ is forbidden kinematically. Let us note that even for $M_H > 350$ GeV the branching ratio of $H \to 2h$ decay is large, however $H$ production cross section becomes small due to the large $H$ mass.

The lighter $H$ the larger its production cross section, however, for $M_H < 250$ GeV the decay $H \to 2h$ is kinematically forbidden. That is why for numerical estimates we took the value $M_H = 300$ GeV for which $H \to 2h$ and $H \to ZZ$ decays dominate\(^2\) and $\Gamma_{H\to2h}/\Gamma_{H\to ZZ} \approx 4$. Thus 300 GeV (or a little bit lighter) $H$ mostly decays to two 125 GeV Higgs bosons.

A technical remark: the equality $\Gamma_{H\to hh} = \Gamma_{H\to ZZ}$ in the limit $M_H \gg M_h, M_H \gg M_Z$ follows from the equality (up to the sign) of $H \to 2h$ and $H \to 2\chi$ decay amplitudes, see [21].

C. $H$ production at LHC

The dominant mechanism of $H$ production is the gluon fusion, cross section of which equals that of SM Higgs production multiplied by $\sin^2 \alpha \approx [(2v_\Delta/v) / (1 - M_h^2/M_H^2)]^2 \approx 2.4 \cdot 10^{-3}$. In Table the relevant numbers are presented. All the numbers correspond to 14 TeV LHC energy.

The subdominant mechanisms of $H$ production are $ZZ$ fusion and associative $ZH$ production. Comparing $ZZh$ and $ZZH$ vertices we will recalculate the cross sections of SM

\(^2\) The decay $H \to ZZ \to (l^+l^-)(l^+l^-)$ provides great opportunity for the discovery of heavy Higgs $H$. 

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TABLE II. The cross sections (QCD NLO) of scalar bosons production in VBF calculated with the help of HAWK (see also Table 10 in [16]).

| $M_h$ (GeV) | 125    | 300    |
|-------------|--------|--------|
| $\sigma_{VV\to h}$ (fb) | 4342(5) | 1418(1) |
| $\sigma_{W^+W^-\to h}$ (fb) | 3272(4) | 1053(1) |
| $\sigma_{ZZ\to h}$ (fb) | 1087(1) | 365(1)  |
| $M_H$ (GeV) | X      | 300    |
| $\sigma_{ZZ\to H}$ (fb) | X      | 0.365(1) |

TABLE III. The cross sections of the associative SM Higgs production from Table 14 in [16] and of associative $H$ production recalculated with the help of (32).

| $M_h$ (GeV) | 125    | 300    |
|-------------|--------|--------|
| $\sigma_{W^*\to Wh}$ (fb) | 1504 ± 4% | 67.6 ± 4% |
| $\sigma_{Z^*\to Zh}$ (fb) | 883 ± 5% | 41.6 ± 5% |
| $M_H$ (GeV) | X      | 300    |
| $\sigma_{Z^*\to ZH}$ (fb) | X      | 0.0416 ± 5% |

processes of $h$ production into that of $H$ production. In SM we have

$$L_{hZZ} = \frac{1}{4} g^2 v Z^2 h.$$ \hspace{1cm} (31)

From (23) we get:

$$\sigma_{ZZ\to H} = \left( \frac{2v_\Delta}{v} \frac{1 - 2M_h^2/M_H^2}{1 - M_h^2/M_H^2} \right)^2 \times (\sigma_{ZZ\to h})^{SM} \approx 10^{-3} \times (\sigma_{ZZ\to h})^{SM},$$ \hspace{1cm} (32)

the same relation holds for $Z^* \to ZH$ associative production cross section.

We separate VBF cross section of SM Higgs production into that in $W^+W^-$ fusion (which dominates) and in $ZZ$ fusion (which is the one that matters for $H$ production) with the help of the computer code HAWK [17]. The obtained results are presented in Table II.

In Table III the results for the associative $ZH$ production cross sections are presented.

We see that gluon fusion dominates $H$ production at LHC. Using model parameters $v_\Delta = 5$ GeV and $M_H = 300$ GeV, we obtain that the branching ratio of $H \to 2h$ decay
equals \( \approx 80\% \). Thus, decays of \( H \) provide \( \approx 20 \text{ fb} \) of double \( h \) production cross section in addition to \( 40 \text{ fb} \) coming from SM. However, unlike SM in which \( 2h \) invariant mass is spread along rather large interval, in the case of \( H \) decays \( 2h \) invariant mass equals \( M_H \).

III. \( H \) PRODUCTION ENHANCEMENT IN GEORGI–MACHACEK VARIANT OF SEE-SAW TYPE II MODEL

The amplitudes of \( H \) production both via \( gg \) fusion and VBF are proportional to the triplet vev \( v_\Delta \) and due to the upper bound \( v_\Delta < 5 \text{ GeV} \) these amplitudes and the corresponding cross sections are severely suppressed.

The triplet vev \( v_\Delta \) should be small in order to avoid the noticeable violation of custodial symmetry which guarantees the degeneracy of \( W \) and \( Z \) bosons in the SM at tree level in the limit \( g' = 0, \cos \theta_W = 1 \). The vacuum expectation value of the complex isotriplet \( \Delta \) with hypercharge \( Y_\Delta = 2 \) violates the custodial symmetry, see \( (8) \). The custodial symmetry is preserved when two isotriplets (complex \( \bar{\Delta} \) and real \( \xi \) with \( Y_\xi = 0 \)) are added to SM and when vev’s of their neutral components are equal \( (11) \). Thus in GM variant of see-saw type II model \( v_\Delta \) is not bounded by \( (10) \) and can be considerably larger. Instead of \( (8) \) in GM model we have:

\[
\begin{align*}
M_W^2 &= \frac{g^2}{4} (v^2 + 4v_\Delta^2), \\
M_Z^2 &= \frac{\bar{g}^2}{4} (v^2 + 4v_\Delta^2),
\end{align*}
\]

and instead of \( (11) \):

\[
v^2 + 4v_\Delta^2 = (246 \text{ GeV})^2.
\]

Note that our \( v_\Delta \) is by \( \sqrt{2} \) bigger than what is usually used in the papers devoted to GM model; our \( v \) is also usually denoted by \( v_\Phi \), while the value \( 246 \text{ GeV} \) is denoted by \( v \).

The scalar particles are conveniently classified in GM model by their transformation properties under the custodial \( SU(2) \). Two singlets which mix to form mass eigenstates \( h \) and \( H \) are:

\[
\begin{align*}
H^0_1 &= \varphi, \\
H^0_2 &= \sqrt{\frac{2}{3}} \varphi + \sqrt{\frac{1}{3}} \xi^0,
\end{align*}
\]

see, for example, \( (18) \). Due to considerable admixture of \( \xi^0 \) in \( H^0_2 \) the \( HW^+W^- \) coupling constant is not suppressed and three modes of \( H \) decays are essential: \( H \to hh, \; H \to W^+W^-, \; H \to ZZ \).
The recently discovered Higgs boson should be identified with $h$. The deviations of $h$ couplings to vector bosons and fermions from their values in SM lead to the upper bound on $v_\Delta$. These deviations in the limit of heavy scalar triplets were studied in a recent paper [18] (see also [19]). From equations (59) and (61) of [18] we get the following estimates for the ratios of the $hVV$ (here $V = W, Z$) and $h\bar{f}f$ coupling constants to that in SM:

$$\begin{align*}
  k_V &\approx 1 + 3 \left(\frac{v_\Delta}{v}\right)^2, \\
  k_f &\approx 1 - \left(\frac{v_\Delta}{v}\right)^2.
\end{align*}$$
(36)

Since at LHC the Higgs boson $h$ is produced mainly in gluon fusion through $t$-quark triangle, for the ratio of the cross sections to that in SM we get:

$$\begin{align*}
  \mu_{\tau\bar{\tau}} &\approx 1 - \left(\frac{2v_\Delta}{v}\right)^2, \\
  \mu_{VV} &\approx 1 + \left(\frac{2v_\Delta}{v}\right)^2.
\end{align*}$$
(37)

Since $h \to b\bar{b}$ decay is studied in associative production, $V^* \to Vh \to Vb\bar{b}$, we get

$$\mu_{bb} \approx 1 + \left(\frac{2v_\Delta}{v}\right)^2.$$  
(38)

Finally in case of $h \to \gamma\gamma$ decay SM factor $16/9 - 7$ in the amplitude is modified in the following way:

$$\frac{16}{9} - 7 \to \left[1 - \left(\frac{v_\Delta}{v}\right)^2\right] \left[\frac{16}{9} \left(1 - \left(\frac{v_\Delta}{v}\right)^2\right) - 7 \left(1 + 3 \left(\frac{v_\Delta}{v}\right)^2\right)\right] =$$
$$= \frac{16}{9} \left(1 - 2 \left(\frac{v_\Delta}{v}\right)^2\right) - 7 \left(1 + 2 \left(\frac{v_\Delta}{v}\right)^2\right),$$
(39)

where the first factor in the first line takes into account damping of $h$ production in gluon fusion.

Let us suppose that $v_\Delta$ is ten times larger than the number used in Section II $v_\Delta^{GM} = 50$ GeV. Then from (34) we get $v_\Delta^{GM} \approx 225$ GeV, and $\mu_{\tau\bar{\tau}} \approx 0.8$, while $\mu_{WW} = \mu_{ZZ} = \mu_{bb} \approx 1.2$. From (39) we get: $\mu_{\gamma\gamma} \approx 1.4$. With the up-to-date level of the experimental accuracy one can not exclude these deviations of the quantities $\mu_i$ from their SM values $(\mu_i)^{SM} \equiv 1$.

One order of magnitude growth of $v_\Delta$ leads to two orders of magnitude growth of $H$ production cross section. Hence 300 GeV heavy Higgs boson $H$ can be produced at 14 TeV LHC with 2 pb cross section which should be large enough for it to be discovered prior

\footnote{We take into account only $t$-quark and $W$-boson loops omitting the loops with charged Higgses.}
to HL-LHC. The search strategy should be the same as for the SM Higgs boson: $gg \rightarrow H \rightarrow ZZ$ decay is a golden discovery mode, the cross section of which can be as large as $(2 \text{ pb}) \times \text{Br} (H \rightarrow ZZ)^{\text{GM}}$, where $\text{Br} (H \rightarrow ZZ)^{\text{GM}}$ depends on the model parameters, see [18].

IV. CONCLUSIONS

The case of extra isotriplet(s) provides rich Higgs sector phenomenology with additional to SM Higgs boson charged and neutral scalar particles. With the growth of triplet vev, production cross section of new scalar grows and the dominant decays of new particles become decays to gauge and lighter scalar bosons. The charged scalars ($\Phi^{++}$, $\Phi^+$) are produced through electroweak interactions. The bounds on the model parameters from nondiscovery of $\Phi^{++}$ and $\Phi^+$ with the 8 TeV LHC data and the prospects of their discovery at 14 TeV LHC are discussed in particular in [20]. In the present paper we have discussed the neutral heavy Higgs production at LHC in which the gluon fusion dominates. $H \rightarrow 2h$ decay contributes significantly to the double Higgs production and even may dominate in the GM variant of the see-saw type II model. The best discovery mode for $H$ is the “golden mode” $pp \rightarrow HX \rightarrow ZZX$, and its cross section can be only few times smaller than for the heavy SM Higgs.

After this paper had been written, paper [21] appeared in arXiv in which the enhancement of double Higgs production due to heavy Higgs decay is considered in the framework of MSSM model with two isodoublets. $H \rightarrow 2h$ resonant decay in MSSM at small tan $\beta$ was previously analyzed in [9].

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