The enhancement of double BEH boson production in the extensions of the Standard Model with extra isotriplets is studied. It is found that in the see-saw type II model decays of new heavy scalar $H$ can contribute to the double $h$ production cross section as much as Standard Model channels. In the Georgi–Machacek model the custodial symmetry is preserved and the strongest limitation on triplet parameters is removed so the production cross section can be much larger while $H \rightarrow ZZ$ and $H \rightarrow WW$ decay channels could be highly suppressed.

1 Introduction

After the discovery of the BEH boson $h$ at the LHC\(^1\) the next steps to check the Standard Model (SM) are the measurement of the coupling constants of the $h$ boson to other SM particles with better accuracy and the measurement of the $h$ self-coupling which determines the shape of the potential. In the SM the triple and quartic couplings are predicted in terms of the known $h$ mass and vacuum expectation value. Deviations from these predictions would mean the existence of New Physics in the $h$ potential. The triple coupling can be measured at the LHC in double $h$ production, in which the gluon fusion dominates: $gg \rightarrow hh$. However, the $2h$ production cross section is very small. At $\sqrt{s} = 14$ TeV the cross section $\sigma^{NLO}(gg \rightarrow hh) = 40.2$ fb with (10 – 15)\% accuracy\(^2\). For the final states with the reasonable signal/background ratios double $h$ production will be found and triple coupling will be measured\(^3\) only at the HL-LHC. We are looking for the extensions of the SM scalar sector in which the double $h$ production is enhanced so it can be tested at the LHC in the next couple of years.

One of the well-motivated examples of non-minimal scalar sector is provided by the see-saw type II mechanism of the neutrino mass generation\(^4\). In this mechanism a scalar isotriplet $(\Delta^+, \Delta^0, \Delta^0)$ with hypercharge $Y_\Delta = 2$ is added to the SM. The vacuum expectation value (vev) of the neutral component $v_\Delta$ generates Majorana masses of the left-handed neutrinos. In this model we get an additional mechanism of the double $h$ production at the LHC in the mode with intermediate new heavy scalar $H$. The $H$ production cross section and its decays widths are proportional to $v_\Delta^2$ so to enhance double $h$ production we need $v_\Delta$ to be as large as possible.

Since the nonzero value of $v_\Delta$ violates the well checked equality of the strength of charged
and neutral currents at tree level, \( \nu_\Delta \) should be less than 5 GeV and this value was used for numerical estimates.

The bound \( \nu_\Delta < 5 \) GeV is removed in the Georgi-Machacek model\(^5\), in which in addition to \( \Delta \) a scalar isotriplet with \( Y = 0 \) is introduced. Bounds on \( \nu_\Delta \) come from the measurement of the 125 GeV boson couplings to vector bosons and fermions, which would deviate from their SM values. Since the accuracy of the coupling measurements is poor, \( \nu_\Delta \) as large as 50 GeV is allowed and \( \sigma (gg \rightarrow H) \) can reach 2 pb value which makes it accessible with the integrated luminosity \( \int L dt = 300 \) fb\(^{-1} \) prior to the HL-LHC run.

The talk is based on results presented in papers\(^6,7\), where more details and references can be found.

## 2 2h production in the see-saw type II model

In this section we consider see-saw type II model and calculate the double \( h \) production cross section. We derive only the necessary formulas (for a detailed description see paper\(^8\)).

In addition to the SM isodoublet field \( \Phi \),

\[
\Phi = \begin{bmatrix} \Phi^+ \\ \phi^0 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} (\nu + \phi + i\chi) \end{bmatrix},
\]

in the see-saw type II an isotriplet is introduced:

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

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

Here \( \bar{\sigma} \) 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

\[
D_\mu \Phi = \partial_\mu \Phi - \frac{ig}{2} A^a_\mu \sigma^a \Phi - \frac{ig}{2} B_\mu \Phi,
\]

\[
D_\mu \Delta = \partial_\mu \Delta - \frac{ig}{2} [A^a_\mu \sigma^a, \Delta] - ig'B_\mu \Delta.
\]

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

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

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:

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

Comparing the result of the SM fit\(^9\), \( M_W^{\text{SM}} = 80.381 \) GeV, with the experimental value, \( M_W^{\text{exp}} = 80.385(15) \) GeV, at 3\( \sigma \) level we get the upper bound \( \nu_\Delta < 5 \) GeV. Since the cross sections we are interested in are proportional to \( (\nu_\Delta)^2 \) we will use this bound for numerical estimates.
The scalar potential is:

\[ V(\Phi, \Delta) = \frac{1}{2} m_\Phi^2 (\Phi^\dagger \Phi) + \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 + M_\Delta^2 \text{Tr} [\Delta^\dagger \Delta] + \frac{\mu}{\sqrt{2}} (\Phi^\dagger \sigma^3 \Delta^\dagger \Phi + h.c.), \] (8)

which is a truncated version of the most general renormalizable potential (see for example eq. (2.6) in paper\(^1\)). The last term in (8) is responsible for generation of \( v_\Delta \).

Quadratic in \( \varphi, \delta \) terms according to (8) are

\[ V(\varphi, \delta) = \frac{1}{2} m_\Phi^2 \varphi^2 + \frac{1}{2} M_\Delta^2 \delta^2 - \mu \varphi \delta. \] (9)

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:

\[
\begin{bmatrix}
\varphi \\
\delta
\end{bmatrix}
= \begin{bmatrix}
\cos \alpha & -\sin \alpha \\
\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
h \\
H
\end{bmatrix},
\tan 2\alpha = \frac{4v_\Delta}{v} \frac{M_\Delta^2}{M_\Phi^2 - m_\Phi^2}, \quad M_h \approx m_\Phi^2, \quad M_H \approx M_\Delta^2.
\] (10)

Since \( \tan 2\alpha \approx 4v_\Delta/v \ll 1 \), the 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. We do not consider here the mixing and masses of other scalar particles which are present in the see-saw type II model since they are not important for \( 2h \) production.

Since \( H \) has a doublet admixture, the dominant mechanism of \( H \) production is the gluon fusion, cross section of which equals that of the SM BEH-scalar production multiplied by \( \sin^2 \alpha \approx [2(v_\Delta/v) / (1 - M_h^2/M_H^2)]^2 \approx 2.4 \cdot 10^{-3} \). In Table 1 the relevant numbers are presented. All numbers correspond to 14 TeV LHC energy. The subdominant mechanisms of \( H \) production are \( ZZ \) fusion and associative \( ZH \) production and they are negligible\(^6\).

### Table 1: The cross sections of \( H \) production via \( gg \) fusion. Values for the SM \( h \) boson are taken from Table 4 in paper\(^11\). All numbers correspond to 14 TeV LHC energy.

<table>
<thead>
<tr>
<th>( M_h ) (GeV)</th>
<th>125</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{gg \rightarrow h} ) (pb)</td>
<td>49.97 ± 10%</td>
<td>11.07 ± 10%</td>
</tr>
<tr>
<td>( M_H ) (GeV)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>( \sigma_{gg \rightarrow H} ) (fb)</td>
<td>300</td>
<td>25 ± 10%</td>
</tr>
</tbody>
</table>

For the decay probabilities we obtain:

\[ \Gamma_{H \rightarrow hh} = \frac{v_\Delta^3 M_H^3}{v^4 8\pi} \left[ \frac{1 + 2 \frac{m_h}{M_H}}{1 - \left( \frac{M_h}{M_H} \right)^2} \right]^2 \sqrt{1 - \frac{M_h^2}{M_H^2}}, \] (11)

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

\[ \Gamma_{H \rightarrow WW} = \frac{v_\Delta^3 M_H^3}{v^4 4\pi} \left[ \frac{M_H^2/M_H}{1 - \left( \frac{M_h}{M_H} \right)^2} \right]^2 \left( 1 - \frac{M_h^2}{M_H^2} + 12 \frac{M_h^4}{M_H^4} \right) \sqrt{1 - \frac{M_h^2}{M_H^2}}, \] (13)

\[ \Gamma_{H \rightarrow hH} = \frac{v_\Delta^3 N_c m_h^2 M_H}{2\pi} \frac{1}{(1 - M_h^2/M_H^2)^2} \left( 1 - \frac{M_h^2}{M_H^2} \right)^{3/2}, \] (14)

where \( N_c = 3 \) is the number of colors.
In the see-saw type II model neutrino masses are generated by the Yukawa couplings of isotriplet $\Delta$ with lepton doublets. These couplings generate $H \to \nu\bar{\nu}$ decays as well. As it was noted in paper$^{12}$ 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, $f \sim m_i/v_\Delta$. That is why for $v_\Delta \gtrsim 1$ GeV leptonic decays are completely negligible. The same holds for decays of charged triplet scalars so direct searches$^{13}$ do not lead to new bounds on model parameters (see also paper$^{14}$).

We suppose that $250$ GeV $< M_H < 350$ GeV so the decay $H \to 2h$ is allowed kinematically while $H \to t\bar{t}$ is forbidden so it does not lead to diminishing of $\text{Br}(H \to 2h)$. But let us note that even for $M_H > 350$ GeV the branching ratio of $H \to 2h$ decay is also rather large, however $H$ production cross section becomes small due to the large $H$ mass. 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$^6$ and $\Gamma_{H \to 2h}/\Gamma_{H \to ZZ} \approx 4$, i.e. the branching ratio of $H \to 2h$ decay equals $\approx 80\%$. Thus, decays of $H$ provide $\approx 20$ fb of double $h$ production cross section in addition to $40$ 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 peaks at $M_H$ which is a distinctive feature of this model (see also paper$^{15,16}$).

3  $2h$ production enhancement in the Georgi–Machacek 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 $v_\Delta < 5$ GeV these amplitudes and the corresponding cross sections are severely suppressed.

The triplet vev $v_\Delta$ should be small in order to avoid 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. The custodial symmetry is preserved when two isotriplets (complex $\xi$ with $Y_\xi = 0$) are added to the SM and when vev’s of their neutral components$^8$ are equal$^5$. Thus in the GM variant of the see-saw type II model $M_W/M_Z = \cos \theta_W$, and $v_\Delta$ is not bounded by 5 GeV. In this model the bound on $v_\Delta$ appears only from measurements of deviations of $h$ couplings to fermions and vector bosons from SM predictions. These deviations in the limit of heavy scalar triplets were studied in the paper$^{17}$ (see also paper$^{18}$).

From equations (59) and (61) of paper$^{17}$ we get the following estimates for the ratios of the $hVV$ (here $V = W$, $Z$) and $hff$ coupling constants to that in the SM:

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

Therefore, for the ratios of the cross sections to that in the SM, we get:

\[
\mu_i \equiv \frac{\sigma}{\sigma_{SM}} \cdot \frac{\text{Br}(H \to 2h)}{\text{Br}_{SM}} = 1 + \mathcal{O}\left(\frac{v_\Delta^2}{v^2}\right).
\]

Since the accuracy in measuring $\mu_i$ is poor, $v_\Delta \approx 50$ GeV is not forbidden. One order of magnitude growth of $v_\Delta$ leads to two orders of magnitude growth of $H$ production cross section. Hence 300 GeV heavy scalar 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 to the HL-LHC.

\footnote{The decay $H \to ZZ \to (t^+t^-) (t^+t^-)$ provides great opportunity for the discovery of heavy scalar $H$.}

\footnote{Note that our $v_\Delta$ is by $\sqrt{2}$ bigger than what is usually used in the papers devoted to the GM model; our $v$ is also usually denoted by $v_\phi$, while the value 246 GeV is denoted by $v$.}
Using coupling constants according to papers \(^1\)\(^7\)\(^,\)\(^14\), for the partial widths of \(H\) decays we get\(^7\)

\[
\Gamma_{H\rightarrow hh} \approx \frac{v_\phi^2 3 M_H^3}{16\pi} \left[ 1 + 2 \left( \frac{M_h}{M_H} \right)^2 \right]^2 \sqrt{1 - 4 \frac{M_h^2}{M_H^2}},
\]

\(\text{(17)}\)

\[
\Gamma_{H\rightarrow ZZ} \approx \frac{v_\phi^2 M_H^3}{48\pi} \left[ 1 - 4 \frac{M_{WW}}{M_H} \right]^2 \left( 1 - 4 \frac{M_{WW}^2}{M_H^2} + 12 \frac{M_{WW}^4}{M_H^4} \right) \sqrt{1 - 4 \frac{M_{WW}^2}{M_H^2}},
\]

\(\text{(18)}\)

\[
\Gamma_{H\rightarrow WW} \approx \frac{v_\phi^2 M_H^3}{24\pi} \left[ 1 - 4 \frac{M_{WW}}{M_H} \right]^2 \left( 1 - 4 \frac{M_{WW}^2}{M_H^2} + 12 \frac{M_{WW}^4}{M_H^4} \right) \sqrt{1 - 4 \frac{M_{WW}^2}{M_H^2}}.
\]

\(\text{(19)}\)

Deriving these formulae we used the approximation \(v_\phi \gg v_\Delta\), i.e. \(\sin 2\alpha \approx 2\sin \alpha\).

Using (17), (18), and (19) for \(M_H = 300 \text{ GeV}\) we get \(\text{Br}(H \rightarrow hh) \approx 98\%\) while \(\text{Br}(H \rightarrow ZZ) \approx 0.6\%\). It means that in spite of large \(H\) production cross section, enhancement in \(ZZ\) final state could be negligible so the search for \(H\) in this mode at the LHC \(^1\)\(^9\) will not lead to new limits on model parameters.

4 Conclusions

The case of extra isotriplet(s) provides rich scalar sector phenomenology with additional to the SM \(h\) 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. In the present paper we have discussed the neutral heavy scalar \(H\) production at the LHC in which the gluon fusion dominates. \(H \rightarrow 2h\) decay contributes significantly to the double \(h\) production and even may dominate in the GM variant of the see-saw type II model.

It was shown that though in the GM model new heavy neutral scalar \(H\) can be produced with large cross section at the LHC, \(ZZ\) and \(WW\) decay modes can be very suppressed (if \(H \rightarrow hh\) decays are kinematically allowed and \(M_H\) is not significantly larger than 300 GeV) so direct searches for \(H\) in these decay modes will not lead to its discovery. This is a peculiar feature of the GM model.

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