Suppression of $H \to VV$ decay channels in the Georgi–Machacek model

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ABSTRACT

The $H \to ZZ$ decay mode is usually considered as one of the most promising ways to discover new heavy neutral scalar H. We show that in the Georgi–Machacek model it is possible to get large enhancement of double SM-like Higgs boson production due to H decays while ZZ and WW decay channels could be highly suppressed.

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1. Introduction

Models with extended Higgs sector provide a very rich phenomenology. In many models there is a heavy neutral scalar H which has the admixture of the neutral component of the Standard Model (SM) doublet. As one of the consequences this new heavy scalar can provide us with the significant enhancement of double SM-like Higgs boson (h) production.

In our previous paper [1] we considered extensions of the SM by isotriplets with hypercharges $Y = 0$ and $Y = 2$. In see-saw type II (one extra triplet with $Y = 2$) double Higgs boson production can be increased by the value which is comparable with what we have in the SM. In the Georgi–Machacek (GM) model [2] we obtained that H production cross section is significantly enhanced so $2h$ production can be much larger than in the SM.

If H is produced with large cross section then in principle it can be discovered in ZZ final state. Direct searches in this mode at the LHC [3] can set limits on model parameters which in some ranges of M_H can be stronger than that from h couplings. However it is not the case in the GM model since we show that $\mathrm{Br}\,(H \to ZZ) < 1\%$ could occur.

2. The model

In the GM model (see [4] for a detailed review of this model[1]) in addition to SM Higgs doublet

$$\Phi^{(0)} = \begin{bmatrix} \Phi^+ \\ \Phi^0 \end{bmatrix}, \tag{1}$$

two isotriplets with hypercharges $Y = 0$ and $Y = 2$ are introduced:

$$\xi = \begin{bmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{bmatrix}, \qquad \Delta = \begin{bmatrix} \Delta^{++} \\ \Delta^+ \\ \Delta^0 \end{bmatrix}. \tag{2}$$

We took the potential in the following form (for a detailed description see [4]):

$$V = \frac{\mu_2^2}{2}\mathrm{Tr}\left(\Phi^\dagger \Phi\right) + \lambda_1 \left[\mathrm{Tr}\left(\Phi^\dagger \Phi\right)\right]^2 + \frac{\mu_3^2}{2}\mathrm{Tr}\left(X^\dagger X\right) - M_1 \mathrm{Tr}\left(\Phi^\dagger \tau^a \Phi \tau^b\right)\left(UXU^\dagger\right)_{ab}, \tag{3}$$

where $\Phi^{(0)}$, ξ and Δ are combined into matrices Φ and X:

$$\Phi = \begin{bmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^{+*} & \Phi^0 \end{bmatrix}, \qquad \langle \Phi \rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} v_\phi & 0 \\ 0 & v_\phi \end{bmatrix}, \tag{4}$$

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[1] We follow the notation used in [4] with minor change: $\chi \leftrightarrow \Delta$, $v_\chi \leftrightarrow v_\Delta$.

$$X = \begin{bmatrix} \Delta^{0*} & \xi^+ & \Delta^{++} \\ -\Delta^{+*} & \xi^0 & \Delta^+ \\ \Delta^{++*} & -\xi^{+*} & \Delta^0 \end{bmatrix},$$

$$\langle X \rangle = \begin{bmatrix} v_\Delta & 0 & 0 \\ 0 & v_\Delta & 0 \\ 0 & 0 & v_\Delta \end{bmatrix}, \qquad (5)$$

U is a rotational matrix:

$$U = \begin{bmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ -\frac{i}{\sqrt{2}} & 0 & -\frac{i}{\sqrt{2}} \\ 0 & 1 & 0 \end{bmatrix}, \qquad (6)$$

$\tau^a = \sigma^a/2$ where σ^a are Pauli matrices. Let us note that we consider simplified potential which corresponds to $\lambda_2, \lambda_3, \lambda_4, \lambda_5$, $M_2 = 0$ choice in the potential considered in paper [4].

The value of v_Δ is generated by the term proportional to M_1 and the following relations are useful:

$$v_\Delta = \frac{M_1 v_\Phi^2}{4\mu_3^2}, \qquad v_\phi^2 + 8 v_\Delta^2 = (246\ \text{GeV})^2. \qquad (7)$$

In paper [1] v_Δ is defined to be $\sqrt{2}$ times larger.

Since the potential is written in the way that vevs of two triplets are the same then the custodial symmetry is preserved and the relation between W and Z boson masses at tree level is the same as in the SM.[2] It means that main restrictions originate from the measurement of h couplings to SM particles. Since the accuracy of these measurements is not very good at the moment, these restrictions are not very tough and v_Δ up to approximately 30 GeV is allowed.

Only one scalar, a combination of ξ^0 and Δ^0, mixes with neutral component Φ^0 of SM doublet forming mass eigenstates, h and H, which correspond to the scalar discovered at LHC (so $M_h = 125$ GeV) and new heavy scalar. Since this new scalar H has doublet admixture, it couples to quarks and therefore it can be produced in gluon–gluon fusion so its production cross section at LHC can be much larger than that for the other scalars of the GM model which can be produced only in electroweak processes. It was stressed in [1] that in some region of parameters space H decays can provide great enhancement of double h production at LHC.

3. Heavy scalar decays

According to papers [4,6] the couplings of H boson to hh, WW, and ZZ are the following:

$$g_{Hhh} = 24\lambda_1 c_\alpha^2 s_\alpha v_\phi - \frac{\sqrt{3}}{2} M_1 c_\alpha \left(3 c_\alpha^2 - 2 \right), \qquad (8)$$

$$g_{HWW} = c_W^2 g_{HZZ} = \frac{g^2}{6} \left(8\sqrt{3} c_\alpha v_\Delta + 3 s_\alpha v_\phi \right), \qquad (9)$$

where $c_W = \cos\Theta_W$, Θ_W is the weak mixing angle, $c_\alpha = \cos\alpha$, $s_\alpha = \sin\alpha$, α is the mixing angle between h and H.

According to the potential (3) α is defined as following:

$$\sin 2\alpha = \frac{-\sqrt{3} v_\phi M_1}{M_H^2 - M_h^2}, \qquad (10)$$

where M_H is the mass of H.

Using coupling constants (8) and (9), for the partial widths of H decays we get

$$\Gamma_{H \to hh} \approx \frac{v_\Delta^2}{v_\phi^4} \frac{3 M_H^3}{8\pi} \left[\frac{1 + 2\left(\frac{M_h}{M_H}\right)^2}{1 - \left(\frac{M_h}{M_H}\right)^2} \right]^2 \sqrt{1 - 4\frac{M_h^2}{M_H^2}}, \qquad (11)$$

$$\Gamma_{H \to ZZ} \approx \frac{v_\Delta^2}{v_\phi^4} \frac{M_H^3}{24\pi} \left[\frac{1 - 4\left(\frac{M_h}{M_H}\right)^2}{1 - \left(\frac{M_h}{M_H}\right)^2} \right]^2$$
$$\times \left(1 - 4\frac{M_Z^2}{M_H^2} + 12\frac{M_Z^4}{M_H^4} \right) \sqrt{1 - 4\frac{M_Z^2}{M_H^2}}, \qquad (12)$$

$$\Gamma_{H \to WW} \approx \frac{v_\Delta^2}{v_\phi^4} \frac{M_H^3}{12\pi} \left[\frac{1 - 4\left(\frac{M_h}{M_H}\right)^2}{1 - \left(\frac{M_h}{M_H}\right)^2} \right]^2$$
$$\times \left(1 - 4\frac{M_W^2}{M_H^2} + 12\frac{M_W^4}{M_H^4} \right) \sqrt{1 - 4\frac{M_W^2}{M_H^2}}. \qquad (13)$$

Deriving these formulae we used the approximation $v_\phi \gg v_\Delta$, i.e. $\sin 2\alpha \approx 2 \sin\alpha$, $\mu_3 \approx M_H$, and $8\lambda_1 v_\phi^2 \approx M_h^2$. For $v_\Delta = 20$ GeV we get $\sin\alpha = -0.35$.

In paper [1] it was found that $H \to hh$ decays can provide large enhancement of double Higgs boson production. For $M_H = 300$ GeV and $v_\Delta \approx 20$ GeV we get $\sigma(gg \to H) = \sin^2\alpha \times \sigma(gg \to H^{SM}) \approx 1.4$ pb at $\sqrt{s} = 14$ TeV. Using (11), (12), and (13) for $M_H = 300$ GeV we get $\text{Br}(H \to hh) \approx 98\%$ while $\text{Br}(H \to ZZ) \approx 0.6\%$. It means that in spite of large H production cross section the enhancement in ZZ final state is negligible so the search for H in this mode at LHC will not lead to new limits on model parameters.

At the same time recent progress in search for hh production [7] makes $H \to hh$ mode the most promising way to search for heavy H in this region of parameter space of the GM model.

4. Conclusions

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 $H \to hh$ 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.

Acknowledgements

References

[1] S.I. Godunov, M.I. Vysotsky, E.V. Zhemchugov, Double Higgs production at LHC, see-saw type-II and Georgi–Machacek model, J. Exp. Theor. Phys. 120 (2015) 369–375.

[2] H. Georgi, M. Machacek, Doubly charged Higgs bosons, Nucl. Phys. B 262 (1985) 463.

[3] V. Khachatryan, et al., CMS Collaboration, Search for a Higgs boson in the mass range from 145 to 1000 GeV decaying to a pair of W or Z bosons, J. High Energy Phys. 2015 (10) (2015) 144 , CMS-HIG-13-031, CERN-PH-EP-2015-074.

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[2] Loop corrections can change this relation due to modification of h couplings. Bounds on deviations of h couplings from the SM is discussed in [5]. In the GM model in the limit $v_\Delta \ll v_\phi$ the coupling of h to weak bosons is modified in the following way: $\kappa_V \approx 1 + 6(v_\Delta/v_\phi)^2$ (see Eqs. (59) and (61) from [4]). For $v_\Delta = 30$ GeV we obtain $\kappa_V \approx 1.09$, and for $v_\Delta = 20$ GeV we find $\kappa_V \approx 1.04$. According to Section 3.4 of [5] it is consistent with experimental data on EWPO.

[4] K. Hartling, K. Kumar, H.E. Logan, The decoupling limit in the Georgi–Machacek model, Phys. Rev. D 90 (2014) 015007.

[5] M. Ciuchini, E. Franco, S. Mishima, L. Silvestrini, Electroweak precision observables, new physics and the nature of a 126 GeV Higgs boson, J. High Energy Phys. 1308 (2013) 106.

[6] Ch.-W. Chiang, K. Yagyu, Testing the custodial symmetry in the Higgs sector of the Georgi–Machacek model, J. High Energy Phys. 2013 (01) (2013) 026.

[7] G. Aad, et al., ATLAS Collaboration, Searches for Higgs boson pair production in the $hh \to bb\tau\tau, \gamma\gamma WW*, \gamma\gamma bb, bbbb$ channels with the ATLAS detector, Phys. Rev. D 92 (2015) 092004 .